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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
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DECEMBER 1923

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THE
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VOLUME LVIII DECEMBER 1923 NUMBER 5

SPECTROGRAPHIC OBSERVATIONS OF MIRA CETI, R LEONIS, T CEPHEI, AND R SERPENTIS

By EDWIN B. FROST and FRANCES LOWATER

ABSTRACT

Reference is made to the results published prior to 1917 by other observers of the spectra of Mira Ceti and R Leonis.

Velocities of Mira Ceti, R Leonis, T Cephei, and R Serpentis.—The velocities of these stars were determined from (*a*) absorption lines, (*b*) bright hydrogen lines, and (*c*) bands of titanium oxide on spectrograms obtained chiefly during the years 1906–1917 at the Yerkes Observatory. Table II exhibits these velocities. A dispersion of three prisms was used for five plates of Mira Ceti, but that of one prism for all of the other thirty-eight plates measured. The velocities obtained from dark lines are approximately constant for each star. The average difference in the velocity of these stars determined from bright and from dark lines is −19.4 km, in close agreement with the differences obtained by other observers (Table III).

A possible explanation of the striking characteristics of the spectra of Md stars.—The difference in the velocities determined from bright and from dark lines, the variation in magnitude and in the maxima may possibly be accounted for by outbursts of hydrogen recurring with considerable regularity.

Bright lines.—The wave-lengths of twenty-four bright lines in addition to those of hydrogen have been determined; although the identification of their sources remains uncertain, their origin would seem to be at comparatively low temperature.

The physical constitution of the stars of class Md, characterized by spectra having dark lines, bright lines and dark bands, offers an interesting field for investigation. One peculiar feature of this class is that the radial velocities determined from the displacement of the dark lines differ systematically from those determined from the bright hydrogen lines, by a quantity of the order of 20 km per second. Another is that the variation in the intensity

of the bright hydrogen lines implies that they disappear when the star's magnitude becomes a minimum. A complete explanation of these phenomena has not yet been found.

Some of the stars of this class were placed on the observing program of the Bruce spectrograph as early as 1906. While no novel results have been obtained, it has seemed desirable to print our study of those for which satisfactory plates are available, particularly Mira Ceti and R Leonis. It will be recalled that the period of Mira is about 331 days, with a range of magnitude from 2.0 to 9.6; and that of R Leonis is 313 days, with a range of magnitude from 4.6 to 10.2. Their maxima and minima are not constant, however, but no regularity in their variation has yet been determined.

Investigations on the spectra of Mira Ceti and R Leonis are found distributed over a period of nearly thirty years. They were assigned to class Md by the Harvard observers.[1]

The most important early papers on these stars are the following:

Harvard Annals, **28**, 45, 98, 108, 1897.

Annie J. Cannon, *ibid.*, **56**, 73, 104, 1912.

W. W. Campbell, *Astrophysical Journal*, **9**, 31, 1899.

W. Sidgreaves, *Monthly Notices*, **58**, 344, 1898; **59**, 505, 1899; **60**, 579, 586, 1900.

A. L. Cortie, *ibid.*, **67**, 534, 1907.

Joel Stebbins, *Lick Observatory Bulletin*, **2**, 78, 1903; *Astrophysical Journal*, **18**, 341, 1903.

V. M. Slipher, *Astrophysical Journal*, **25**, 66, 235, 1907.

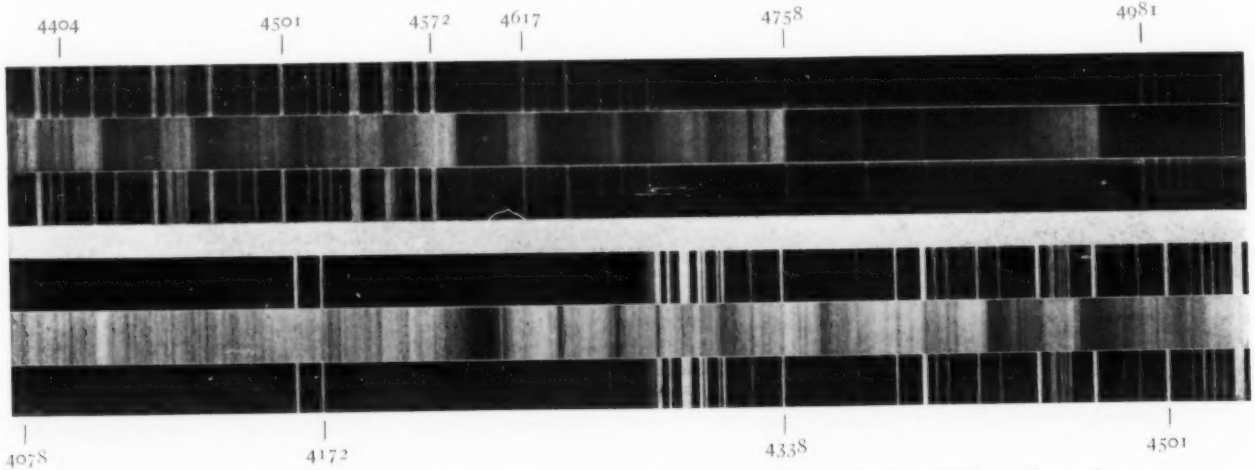
J. S. Plaskett, *Journal of the R.A.S. of Canada*, **1**, 45, 1907.

P. W. Merrill, *Publications of the Astronomical Observatory of the University of Michigan*, **2**, 45 ff., 1916; *Astrophysical Journal*, **41**, 247, 1915.

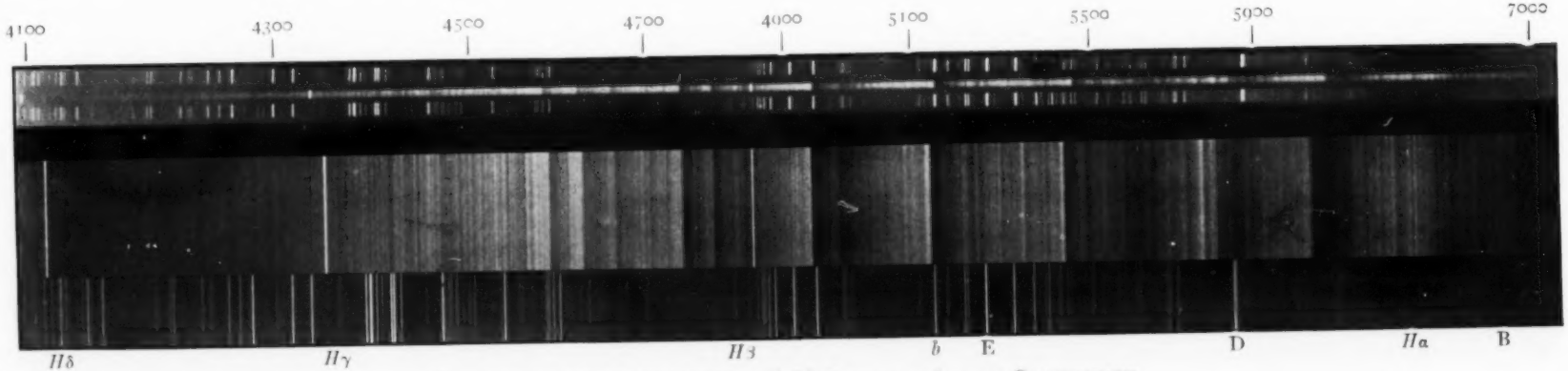
The spectrum of Mira Ceti is shown in Plate V, which is reproduced from this *Journal* (**25**, 236, 1907, *q.v.*) where it illustrated a short paper on Mira Ceti by Dr. V. M. Slipher, who has cordially assented to its reproduction here. The spectrum of R Leonis is reproduced, also on Plate V, from a vertical enlargement by Professor S. B. Barrett of our one-prism spectrogram No. IB 1004,

[1] According to the modified Harvard classification adopted at the Rome meeting (*Transactions of the International Astronomical Union*, **1**, 103, 1922; reprinted in this *Journal*, **52**, 65, 1923), the spectrum of Mira should be designated as M6e at maximum, and as Mvep! at minimum.

PLATE V



SPECTRUM OF R LEONIS TAKEN BY PARKHURST AND SULLIVAN. COMPARISON SPECTRUM OF *Ti* AND *Fe*



SPECTRUM OF MIRA CETI TAKEN BY V. M. SLIPHER AT LOWELL OBSERVATORY

The upper spectrum is a five-fold direct enlargement of the original negative; the lower one is a vertical enlargement of the same on a slightly smaller horizontal scale. The comparison lines are of *V*, *Fe*, and *Na*.

taken by Parkhurst and Sullivan about a week after maximum; for a comparison, the spark spectrum of titanium and iron was used.

The velocities of these stars, determined from their dark spectral lines, are approximately constant, that of Mira being about +67 km per second, and that of R Leonis +18 km per second. The velocities obtained by different observers are collected in Table III.

Among the points dealt with in the above investigations, aside from determination of velocity and structure of bright lines, are the following.

The wave-lengths of the heads of the bands in the spectrum of Omicron Ceti and of some other stars were determined by Stebbins and by Plaskett. (At that time sufficient evidence for the identification of these bands was not available.)

The difference in the displacement of the bright lines and of the dark lines, the former being approximately 0.25 A less toward the red than the latter, was noted by all of the observers.

Stebbins made a study of the changes in the intensity of the bright lines and of the continuous spectrum as the stars grew fainter, which indicated that the intensity of the bright hydrogen lines decreased with the decrease in magnitude of the star, while that of a few other bright lines increased; the later plates furnished evidence which supported the view that the bright hydrogen lines disappeared when the star was at minimum.

In measuring the spectrograms secured here our plan was: To determine the radial velocity of the stars from the displacement (*a*) of absorption lines, (*b*) of bright lines, and (*c*) of absorption bands; to find, if possible, the explanation of the difference in the velocity determined from these three kinds of spectra; and to identify the sources of numerous bright lines and of a few unknown absorption lines.

The spectra were photographed by different observers with the Bruce spectrograph attached to the 40-inch refractor; for the majority of the plates, the dispersion of one prism was used; for a few, three prisms were employed.

The region well covered by the three-prism plates extends from λ 4338 to λ 4885; by the one-prism plates from λ 3860 to λ 5036.

The magnitudes given in the last columns of Tables I and II are from the observations published in the *Memoirs* of the British Astronomical Association, **17–18,** 1910–1912. For 1915 to 1919 the magnitudes are taken from the monthly reports of the American Association of Variable Star Observers, published in *Popular Astronomy*.

Table II gives the results of measurement of thirty-one plates of Omicron Ceti, eight of R Leonis, two of T Cephei, and two of R Serpentis, which include practically all the plates of these stars suitable for accurate measurement which were available in 1917 (later continued through 1920). The columns headed "Number of Lines" or "Number of Bands" show the number of lines or bands used in the determination of the velocity. Of course all velocities have been reduced to the sun.

The plates were measured with the Gaertner comparator and reduced by the method ordinarily practiced here of calculating the constants of a Hartmann formula for each spectrogram.

It is evident from the fourth and sixth columns of Table II that no material difference in the velocity of Mira Ceti has been introduced by the use of different spectral lines in the greater extension to the violet of the plates of low dispersion. The mean velocity of Mira obtained from dark lines, when equal weight is given to all the 18 plates, is $+67.1\pm0.53$ km; from bright hydrogen lines on 30 plates, it is $+49.2\pm0.59$ km. The number of plates is too small to warrant us in attaching significance to the difference in the velocity from dark lines, $+64.2$ km, from the three-prism plates taken in December 1906, and the velocity, $+70.0$ km, from the one-prism plates taken in January 1907. However, there may be some physical significance in the difference in the velocity of $+45.4\pm0.73$ km, obtained from bright lines soon after the maximum at magnitude $2^{M}3$, in December 1906, and the velocity of $+53.1\pm0.27$ km obtained from bright lines soon after the fainter maximum at $3^{M}6$ in February 1915; and again in the difference of the former velocity and the velocity of $+51.5\pm0.89$ km after the fainter maximum of $3^{M}6$ in September 1917. This point will be discussed later.

TABLE I

JOURNAL OF OBSERVATIONS

MIRA CETI

No. of Plate	Date	G.M.T.	Duration	Hour Angle	Quality	Observers	Magnitude
IIIB 677*.....	1906, Dec. 22	13^h02^m	150^m	E 1^h10^m	f.	F, P, S	2.3
679.....	23	13 27	206	E 0 37	g.	F, P, S	
686.....	24	12 54	40	E 1 05	v.g.	F, P, B	
687.....	25	11 43	18	E 2 13	v.ft., L.g.		
688.....	25	12 20	12	E 1 36	f.	F, I	
IB 942†.....	1907, Jan. 5	14 55	5	W 1 42	f.	F, Fox, S	2.5
943.....	5	15 09	18	W 1 57	g.	F, Fox, S	2.5
944.....	5	15 29	0^m40^s	W 2 16	L.g.	F, Fox, S	2.5
952.....	25	13 54	30	W 2 02	g.	F, S	3.0
953.....	25	14 17	6	W 2 24	L.g.	F, S	3.0
954.....	25	14 24	2^m30^s	W 2 31	L.g.	F, S	3.0
972.....	Feb. 8	13 03	42	W 2 05	L.f.	F	4.0
3903.....	1915, Jan. 29	12 50	75	W 1 12	v.g.	My, S	3.8
3904.....	29	13 41	10	W 2 03	v.g.	My, S	3.8
3998.....	Feb. 8	13 10	64	W 2 13	g.	F, S	3.5
3999.....	8	13 52	10	W 2 55	f.	F, S	3.5
4009.....	16	12 55	62	W 2 29	v.g.	F	3.8
4357.....	1916, Jan. 17	12 05	35	E 0 19	v.g.	B, H	3.3
4381.....	23	12 06	30	W 0 06	L.g.	H, F	3.7
5095.....	1917, Nov. 16	15 11	52	E 1 17	g.	Wk, S, B	4.0
5103.....	23	15 08	75	E 0 53	v.g.	Wk, S	4.0
5115.....	Dec. 10	14 18	100	E 0 34	g.	B, Wk	4.6
5145.....	1918, Jan. 4	11 50	48	E 1 22	L.g.	Wk, B	5.2
5378.....	Sept. 16	21 07	60	W 0 37	v.g.	Wk, S	3.7
5389.....	30	20 15	61	W 0 42	g.	Wk, S	3.9
5575.....	1919, Aug. 18	20 22	45	E 2 04	g.	Wk, S	3.3
5581.....	29	21 36	45	E 0 10	L.g.	B, S	3.4
5591.....	Sept. 12	18 34	50	E 2 12	f.	B, S	
5595.....	15	19 19	62	W 0 45	L.g.	B, P_V, S	3.9
5894.....	1920, Aug. 2	21 21	100	E 1 57	L.g.	Bk, J, S	
5955.....	25	21 17	90	E 0 36	f.	B, S	4.8

Maxima of Mira.... {1906, Dec. 18, 2^M3 — 1916, Nov. 8, 3^M6 — 1919, Aug. 8, 3^M0
{1915, Feb. 8, 3.5 — 1917, Oct. 15, 3.6 — 1920, July 5 (Too near sun)
{1915, Dec. 22, 3.0 — 1918, Sept. 16, 3.6

R LEONIS

IB 738.....	1906, Apr. 21	14^h30^m	65^m	W 0^h48^m	v.ft., L.g.	P, S	6.1
739.....	21	16 20	35	W 2 35	L.g.	P, S	6.1
741.....	23	15 21	64	W 1 50	L.v.g.	F, S	6.0
747.....	27	15 50	105	W 2 32	L.g.	B, S	6.3
752.....	28	15 45	223	W 2 32	f.	P, S	6.3
782.....	June 2	15 00	78	W 4 09	p.	P, S	6.9
1004.....	1907, Feb. 24	19 51	210	W 2 00	v.g.	P, S	5.7
1011.....	Mar. 31	18 08	210	W 3 05	g.	F, P	6.5

Maximum of R Leonis: 1906, April 1, 5^M6.

T CEPHEI

IB 783.....	1906, June 2	17^h00^m	120^m	E 5^h20^m	ft.	P, S	6.0
785.....	9	16 28	225	E 5 23	f.	P, S	6.3

Maximum about May 24, 1906, at 6^M3

R SERPENTIS

IB 788.....	1906, June 24	18^h11^m	221^m	W 2^h42^m	f.	P, S	7.2
790.....	30	16 04	172	W 0 59	f.	P, S	7.2

Maximum about July 14, 1906, at 6^M9

Symbols: f. = fair; ft. = faint; g. = good; L. = bright lines of hydrogen; p. = poor; v. = very.
Observers: B = Barrett; Bk = Miss Block; F = Frost; H = Hubble; I = Ichinohe; J = M. F. Jordan; My = Maney; P = Parkhurst; P_V = Paraskévopoulos; S = Sullivan; Wk = Miss Wickham.

* Plates IIIB 677 to 688 were obtained with three prisms.

† Plates IB 942 to 5955 were obtained with one prism.

TABLE II

Radial Velocities for Mira Ceti

Plate	Date	Dark Lines: All Suitable No. of Lines	Dark Lines: All Suitable Km	Dark Lines: Lines Common* No. of Lines	Dark Lines: Lines Common* Km	Bright Lines of Hydrogen No. of Lines	Bright Lines of Hydrogen Km	Bands of Titanium Oxide No. of Bands	Bands of Titanium Oxide Km	Meas. By	Magnitude	Maxima
IIIB	1906											1906
077	Dec. 22	24	+63.7	3	+71	1	+54	.....	.....	F	2.3	Dec. 18
079	23	22	63.2	4	64	.....	.....	.....	.....	F	.....	2.3
086	24	24	65.1	4	67	2	44	4	+49	L	.....	.....
087	25	7	64.9	.....	.....	2	44	.....	.....	F	.....	.....
088	25	.....	.....	.....	.....	2	39	.....	.....	F	.....	.....
Mean (3 prisms)		.....	+64.2	.....	+67	.....	+45	.....	+49	.....	.....	.....
IB	1907											
942	Jan. 5	6	+67	3	+68	3	+47	4	+54	L	2.5	.....
943	5	6	74	4	74	3	46	4	44	L	.....	.....
944	5	.....	.....	.....	.....	3	45	.....	.....	L	.....	.....
952	25	9	69	.....	.....	3	47	4	47	L	3.0	.....
953	25	.....	.....	.....	.....	3	43	.....	.....	F	.....	.....
954	25	.....	.....	.....	.....	3	44	.....	.....	F	.....	.....
954	25	.....	.....	.....	.....	3	40	.....	.....	L	.....	.....
972	Feb. 8	.....	.....	.....	.....	3	45	.....	.....	F	4.0	.....
Mean (1 prism)		.....	+70	.....	+71	.....	+45	.....	+48	.....	.....	.....
IB	1915											1915
3993	Jan. 29	18	+66.9	4	+65	2	+53	3	+41	F	3.8	Feb. 8
3994	29	.....	.....	.....	.....	3	50	.....	.....	F	.....	3.5
3994	29	.....	.....	.....	.....	2	56	.....	.....	L	.....	.....
3998	Feb. 8	18	68.4	4	69	2	53	4	53	L	3.5	.....
3999	8	.....	.....	.....	.....	2	54	.....	.....	F	.....	.....
3999	8	.....	.....	.....	.....	2	55	.....	.....	L	.....	.....
4009	16	16	74.7	3	77	2	52	4	56	L	3.8	.....
Mean		.....	+70	.....	+70	.....	+53	.....	+50	.....	.....	.....
IB	1916											1915
4357	Jan. 17	8	+66	4	+67	3	+46	4	+44	L	3.3	Dec. 22
4381	23	.....	.....	.....	.....	3	47	.....	.....	H	3.7	3.0
IB	1917											Sept. 27
5095	Nov. 16	.....	.....	.....	.....	2	52	.....	.....	L	.....	3.6
5103	23	14	+64	.....	.....	4	54	.....	.....	Wk	.....	.....
5115	Dec. 10	17	69	.....	.....	3	53	8	62	L	4.0	.....
		16	64	.....	.....	4	48	.....	.....	Wk	.....	.....
		29	67	.....	.....	3	50	6	53	L	4.6	.....
5145	1918 Jan. 4	.....	.....	.....	.....	2	56	.....	.....	Wk	.....	.....
Mean		.....	+66	.....	.....	.....	+53	.....	+58	.....	.....	.....
IB	1918											Sept. 16
5378	Sept. 16	16	+69	.....	.....	2	52	.....	.....	L	3.7	3.6
5389 (2)	30	25	66	.....	.....	2	52	6	+64	L	3.9	.....
Mean		.....	+68	.....	.....	.....	+52	.....	+64	.....	.....	.....

* This includes only lines common to both three-prism and one-prism plates.

TABLE II—*Continued*

Plate	Date	Dark Lines				Bright Lines of Hydrogen		Bands of Titanium Oxide		Meas. by	Magnitude	Maximum
		All Suitable		Lines Common*								
		No. of Lines	Km	No. of Lines	Km	No. of Lines	Km	No. of Bands	Km			
IB	1919											Aug. 8
5575	Aug. 18	20	+69			3	+45			L	3.3	3.0
5581	29					3	44			L	3.4	
5591	Sept. 12	8	71			3	50	5	46	L		
5595	15					2	49			L	3.9	
Mean			+70				+47					
IB	1920											
5894	Aug. 2					2	59			L		
5955	25	13	+61				+50		58	L	4.8	
R LEONIS												
IB	1906											
738	Apr. 21					2	− 6.3			F		
739	21					2	4.5			F		
739	21					2	2.4			L		
741	23					2	7.0			F		
741	23					2	7.6			L		
747	27					2	6.7			L		
752	28	11	+19			2	6.2			L		
782	June 2					2	10.8			F		
	1907											
1004	Feb. 24	11	16			2	7.5			L		
1011	Mar. 31					2	1.5			F		
Mean			+18				− 6.0					
T CEPHEI												
IB	1906											
783	June 2	5	−15			2	−33	3	−83	L		
785	9	7	−13			2	−28	3	−69	L		
Mean			−14				−30		−76			
R SERPENTIS												
IB	1906											
788	June 24	6	+32			2	+15	3	−69	L		
790	30	5	+28			2	+ 6	3	−45	L		
Mean			+30				+10		−57			

The velocity has been computed from the displacements of the bands of titanium oxide, with the use of the wave-lengths given by A. Fowler[1] when he proved this compound to be the chemical origin of the bands characteristic of the spectra of stars

[1] *Proc. Roy Soc.*, A, **79**, 509, 1907.

of class Md. We see from Table II that this velocity differs little from that obtained from bright hydrogen lines, being $+51.6 \pm 1.3$ km. However, some uncertainty must be attached to the velocity determined from the heads of bands on account of the difficulty of setting on the head or the corresponding parts of a head on the stellar absorption plate and the laboratory emission plate; for more reliable values we need many plates of high dispersion and with exposure of the stellar plates most suitable for absorption bands.

A further attempt to find the velocity from the bands of titanium oxide was made by Miss Lowater while working recently under

TABLE III

COMPARISON OF VELOCITIES OBTAINED BY DIFFERENT OBSERVERS

STAR	VELOCITY FROM		DIFFERENCE BRIGHT − DARK	OBSERVERS	EPOCH
	Dark Lines	Bright Lines			
	km	km	km		
Mira Ceti.....	+62 (7)	+44 (7)	−18	Campbell and Wright	1897–98
	+66 (7)	.....	.....	Stebbins	1902
	+63 (1)	+48 (1)	−15	Campbell and Stebbins	1914
	+67 (3)	+52 (4)	−15	Merrill	1914
	+65 (2)	+46 (14)	−19	Plaskett	1906–7
	+67 (18)	+49 (30)	−18	F. and L.	1906–7, 1915,1916, 1917,1918, 1919,1920
R Leonis.....	+25 (2)	0 (7)	−25	Merrill	1914
	+18 (2)	− 6 (8)	−24	F. and L.	1906, 1907
R Serpentis.....	+32 (1)	+ 8 (4)	−24	Merrill	1914
	+30 (2)	+10 (2)	−20	F. and L.	1906
T Cephei.....	.....	−30 (2)	.....	Merrill	1914
	−14 (2)	−30 (2)	−16	F. and L.	1906
		Mean	−19.4		

Mean of differences for all stars by all observers $= -19.4$ km
Mean of differences for all stars by F. and L. $= -19.5$ km
The numbers of plates used in forming the mean are given in parentheses after the velocities.

Professor Fowler in the Astrophysical Laboratory of the Imperia College of Science, London. The emission spectrum of titanium oxide was photographed with a Littrow spectrograph, giving resolution of the same order as that of the stellar plates. A negative enlargement of the three-prism laboratory plate to represent absorption was made on the same scale as an enlarged positive of

the corresponding stellar spectrogram. Comparison of these enlargements showed more numerous coincidences of band lines in the stellar and laboratory plates than was previously suspected. For determination of wave-lengths of band lines the stellar spectrogram was not very suitable, but a study of these enlargements strongly suggests that the displacement, due to velocity of the lines of the band cannot be very different from that of the metallic lines common to the two spectra.

The results of the present investigation confirm the conclusions of other observers:

1) that the velocity of these stars is practically constant;

2) that the velocity determined from bright hydrogen lines has a much smaller positive value than that from dark lines, of the order of 20 km per second.

The recession of Mira Ceti being 67 km and that of the radiating hydrogen 49 km, the star may be considered to be at rest and the luminous gases to be leaving the star with a velocity of 18 km relatively to its surface. A possible explanation of the difference in the radial velocity, according as it is determined from the displacement of dark lines or bright hydrogen lines, would thus be found in the eruption or shooting outward of hydrogen, as is well known to occur in the eruptive solar prominences. The evidence in support of this explanation is as follows:

1. Velocities far in excess of 20 km per second have been observed in the ascent of eruptive solar prominences. If hydrogen is erupted from the stars in the direction of the line of sight, the velocity determined from its lines would have a smaller positive or a larger negative value than that obtained from dark lines. Hydrogen erupted in directions inclined to the line of sight at angles ranging from zero to 90° would have a component of its velocity varying from the maximum to zero kilometer per second. This variation in velocity would cause a broadening of the bright hydrogen lines, which is in evidence on the plates, although probably lost in the intrinsic breadth of these bright lines. The widths of the bright hydrogen lines in Mira are shown in Table IV. Thus this explanation finds support in the order of magnitude of the difference in velocity obtained from dark and bright lines.

TABLE IV

WIDTHS OF BRIGHT HYDROGEN LINES

Plate	Width in km per sec.		
	λ 3889.201	λ 4101.890	λ 4340.634
IB 5095	.....	94	91
5145	.....	51	69
5103	57	114	105
5115	62	104	99

2. It receives support in regard to periodicity from the evidence obtained by Stebbins, that the bright hydrogen lines disappear at a minimum, combined with the fact that eruptive prominences of the sun are most numerous at the times of sun-spot maxima; since these are periodic, the frequency of eruptive prominences must be of a periodic character.

3. Not only is there need of an explanation of the difference in velocity from dark and bright lines, but also for the variation in the magnitude of the stars, and for the variation in the values of their maxima. The variation in the brightness of Mira has not been accounted for by the presence of any companion. Stebbins has expressed the opinion that the star's variation is due to the action of internal forces. Since it is probable that the eruption of hydrogen is periodic and there is evidence of the hydrogen lines disappearing at a minimum, it is possible that the variation in magnitude itself is due to the eruption of luminous hydrogen, the magnitude increasing with the larger quantities or the greater heights of ascent of the gas. The variation in the maxima may depend on the speed with which this incandescent gas is projected. Presumably the greater its speed, the greater will be the distance outward that it will travel through the heavier envelopes of the star, and then the light which it emits will be subject to less general absorption than when its speed is less. This idea is suggested by the occurrence of a smaller difference in the velocity from dark and bright lines in January and February, 1915, when it was 17 km, and in November and December, 1917, when it was 14 km, than in January, 1907, when it was 25 km; at these times the maxima were 3.8, 3.6, and 2.3 respectively, differing by 1.5 and 1.3 magnitudes.

4. The spectrum of the solar prominences contains bright lines of hydrogen, helium, and some metals; the spectra of Mira Ceti and R Leonis also contain lines of those elements.

It is not at all probable that the difference in displacement of the dark lines and the bright hydrogen lines is due to pressure, for the pressure in the sun's atmosphere has recently been shown to be about one thousandth of an atmosphere, and that of the stars' is probably of the same order of magnitude.

BRIGHT LINES

Hydrogen lines.—In the spectrum of *o* Ceti, Hβ and Hγ appeared on all but one of our thirty-one plates; on that one, IB 4009, Hβ may have been masked by continuous spectrum. Hδ was present on all the one-prism plates, but was not within the range of the three-prism plates. Hζ was on all the one-prism plates except those which were given short exposures and showed bright lines only. Hϵ appeared unmistakably on one plate only, namely, IB 952, taken on January 25, 1907, or about forty days after the star's maximum.

In the spectrum of R Leonis Hβ and Hϵ were entirely invisible; Hγ and Hδ were present on all the plates, but Hζ was visible on only four of the eight plates measured.

Other bright lines.—The wave-lengths of the other bright lines are contained in Table V; they have been corrected for the displacement due to the velocity determined from the bright hydrogen lines. In seeking to identify their sources we have compared their wave-lengths with Rowland's "Preliminary Table of Solar Spectrum Wave-lengths," with corrections and additions to date; with Exner and Haschek's *Codex*, and with the table of iron lines in Kayser's *Handbuch der Spectroscopie*, **6**; also with the tables in Kayser's *Handbuch*, **5** and **6**, containing the wave-lengths of lines of the elements enumerated in Table VI; with data by Eder and Valenta; with wave-lengths of flame lines by Sir Norman Lockyer and by others; also with those of electric furnace spectra by King, and of enhanced lines by Fowler and by Baxandall.

The evidence from a comparison of stellar and laboratory lines, as far as its goes, might suggest that most of the bright lines arise

from the rarer elements, namely, Tm, Ce, Wo, Y, Ta, Tr, Kr, Pr, Ru; Ti and V are also suggested, as are the more common elements, Fe, Ca, Mn, Ni, Cr, and H giving its secondary spectrum.

TABLE V

BRIGHT LINES IN THE SPECTRA OF *o* CETI AND R LEONIS, EXCEPT HYDROGEN LINES

Weighted Mean Wave-Length	Weighted Mean Wave-Length
3905.78	4511.73
4103.15	4521.54
4138.80	4559.88
4166.03	4562.15
4202.01	4584.08
4206.68	4633.72
4233.42	4634.94
4375.98	4639.26
4454.41	4756.72
4457.06	4801.33
4458.79	4803.18
4461.44	4838.68

TABLE VI

He	Mg	Sc	C	N	O	Mn	Ru
Ne	Ca	Y	Si	V	Cr		
Ar	Sr	La	Ti	Nb	Wo		
Kr	Ba		Zr	Ta			
Xe			Ce				

Also the rarer elements, of which the place in the Mendeléjef table is not yet fixed, namely, Pr, Nd, Sa; Eu, Gd, Tb; Dy, Nh, Er, Tm, Ny, Lu.

The correction applied to the wave-lengths of the unknown bright lines may not have reduced their measured wave-lengths correctly, for the difference in Mira's velocity determined from the bright hydrogen lines and from the absorption lines is presumably due to motion of the gas, and the sources of the other bright lines may move with a velocity less than that of hydrogen. If that be so, the wave-lengths of lines from different sources would have errors of different magnitudes, but for the lines from any one source we should have approximately equal errors, equal differences between the stellar and laboratory values of the wave-lengths. This test has been carefully applied to the lines of many metals and gases, but no consistent differences found.

Further, in cases where the wave-lengths of a few stellar lines approximate fairly consistently to the laboratory values of metallic lines, they represent only the weaker lines of the metal, the prominent lines of corresponding temperature not being found. For example, if we have the low temperature iron lines λλ 4202.2, 4216.4, 4376.1, and 4461.8, we should also find the intense lines λλ 4383.7, 4404.9, 4415.3, also of low temperature. The same criticism applies to two lines approximating those of nitrogen, λ 4511.73 and λ 4634.94. Again, our line λ 4166.03 is temptingly near the barium line λ 4166.161, and if it represents barium we should also find the line λ 4130.68, a member of the same triplet, but of twice the intensity of the former line; of that, however, we have no record.

In regard to temperature as a guide in identification, the recent work by A. S. King,[1] "On the Production of the Titanium Oxide Bands in the Electric Furnace," indicates a state of comparatively low temperature in the star, rather than high. Work by Nicholson and Pettit[2] leads to the same conclusion. This evidence is confirmed by work done by Miss Lowater on the bands of titanium oxide produced in the arc, showing that it is necessary to keep the current small, from two to three amperes, in order to maintain the bands comparatively free from titanium lines. This evidence of low temperature is in direct opposition to the existence of enhanced lines, as for instance, the iron lines λ 4233.3 and λ 4584.0 in the spectra of stars of type M. These enhanced lines characterize B-type stars in the spectra of which, as is well known, no bands of titanium oxide are found. The evidence is that the bands of titanium oxide cannot co-exist with enhanced lines. If the bright lines are high temperature lines, it would seem that they must arise from a body separated from the source of the bands.

We are strongly inclined to the opinion that identification of these bright lines will not be found among terrestrial metals, rather more likely among gases. It may, however, be an unknown spectrum.

The identification will surely remain uncertain until we can obtain more accurate determinations of the wave-lengths of the

[1] *Publications of Astronomical Society of the Pacific*, **34**, 348, 1922.

[2] *Ibid.*, **34**, 132, 1922.

bright stellar lines. A comparison of the tables of Stebbins,[1] of Adams and Joy,[2] and of ourselves, makes this point very evident: within the region common to the three tables Stebbins has four lines, and Adams and Joy eight, which we have not; we have nineteen lines not in the list of Adams and Joy, and another not in Stebbins' list; further, among those lines which we have in common, the differences in wave-length of lines apparently the same are quite inconsistent and cannot be accounted for by the application of different corrections or by the use of different standards. Can these differences be accounted for by changes in the star, which are accompanied by the change in magnitude?

It may be of interest to call attention to the appearance, on plates of long exposure of Mira and of R Leonis, of a bright line of comparatively small intensity on the less refrangible side of Hδ; its appearance and proximity to Hδ suggested to us long ago the name "Fratello." Its mean wave-length is λ 4103.15±0.015, when corrected for the star's velocity determined from the bright hydrogen lines. Comparison of the two silicon lines given by Rowland at λ 3905.660 and λ 4103.097 with our lines λ 3905.78 and λ 4103.15, shows a discrepancy of 0.07 A in the difference in wave-length of the two solar lines and of the two stellar lines. It is just such a discrepancy which makes their identification with silicon uncertain.[3]

Absorption lines.—The elements represented by the dark lines from which the velocity was determined are: Mg, Ca, Sr, Ba; Ti, Zr; V; Cr; Mn; Fe and Ni.

SUMMARY

The results of the present measurements may be summarized as follows, the first and second items apparently confirming the results of other observers:

1. The radial velocities of the stars *o* Ceti and R Leonis are constant.

[1] *Lick Observatory Bulletin*, **2**, 78, 1903.

[2] *Publications of Astronomical Society of the Pacific*, **30**, 193, 1918.

[3] But see the recent comments on the identification of these lines by F. E. Baxandall in the *Observatory*, **46**, 226, July, 1923, which seem to establish the certainty of their identification with silicon.

2. The difference in the displacement of the dark lines and of the bright hydrogen lines is equivalent to a negative velocity of the order of 20 kilometers per second.

3. Possibly the variation in the magnitude of these stars and in their maxima may be accounted for by outbursts of hydrogen, occurring with considerable regularity as to time; possibly also these may account for the difference in the velocities determined from bright and dark lines.

This paper was prepared for publication in essentially its present form in 1917, but was withheld in the hope of obtaining some satisfactory explanation of the phenomena involved; and was further delayed by the prospect of Miss Lowater's work in London, hence it might without impropriety be dated 1917. It thus does not discuss the interesting observations, chiefly made at Mount Wilson since that date. Since the paper was in type, Joy and Humason have detected a faint companion to Mira of magnitude about 10, with a spectrum of type B or earlier and showing bright lines. This companion has been seen and measured by Aitken, by Van Biesbroeck, and by others. But this does not appear to account for the spectrum of Mira at maximum, although greatly assisting in explaining the anomalous spectrum found at Mount Wilson when it is near minimum.

We wish to express our thanks to Professor A. Fowler for his valuable suggestions pending the publication of this paper while Miss Lowater has been working on closely related subjects in his laboratory at the Imperial College of Science and Technology during 1922–1923.

YERKES OBSERVATORY
November 1923

ARC AND SPARK SPECTRA OF ALUMINUM, ZINC, AND CARBON IN THE EXTREME ULTRA-VIOLET

By R. O. HUTCHINSON

ABSTRACT

Description of apparatus and methods employed.—A grating spectrograph, inclosed in a metal tube which could be evacuated, was used. Evacuation of the tube was effected with a mercury diffusion pump. The arc was struck by means of an electromagnet at definite intervals and exposure completed in about twenty minutes, the arc being operated at less than 110 volts. The spark was produced by an induction coil operated as a transformer on the 110-volt alternating potential. The exposure required about two or three hours.

Tables of lines measured.—The arc spectra of aluminum, zinc and carbon to λλ 696, 768, and 595, and the corresponding spark spectra to λλ 678, 467, and 460 were measured and the intensities of the lines compared. This represented an extension of the arc spectra of metals from λ 1376 to λ 595.

INTRODUCTION

The spark spectra of aluminum, zinc, carbon, and many other substances have been measured in this laboratory and extended far into the extreme ultra-violet by the work of Millikan, Sawyer, and Bowen[1] using the vacuum spectrograph. Various attempts have been made to extend the arc spectra of metals into the extreme ultra-violet. Wolff,[2] using a prism vacuum spectrograph and a vacuum arc separated from the spectrograph by a fluorite window, obtained the spectrum of zinc to λ 1376. McLennan, Ainslie, and Fuller,[3] using a fluorite prism spectrograph, measured the spectrum of aluminum to λ 1605, of carbon to λ 1464, and of zinc to λ 1445. Saunders[4] used a vacuum grating spectrograph but had his source of light and his photographic plate both outside, so that the light had to pass through two quartz plates. He photographed the arc and spark spectra of aluminum, zinc, and a few other substances

[1] *Astrophysical Journal*, **52**, 286, 1920; **53**, 150, 1920. *Proceedings of the National Academy of Sciences*, **7**, 289, 1921.

[2] Lyman, *The Spectroscopy of the Extreme Ultra-Violet*, p. 96. 1914.

[3] *Proceedings of the Royal Society*, **95**, 316, 1919.

[4] *Astrophysical Journal*, **43**, 234, 1916.

above λ 1670. McLennan and Lang,[1] using a vacuum grating spectrograph with the arc on the inside, were able to get the arc spectrum of carbon as far as λ 584, but were unable to go lower than λ 1427 with a metallic arc. They said they could get no lines below λ 2000 with an intermittent arc. They do not claim any great accuracy for their measurements.

The present investigation was started for the purpose of extending the arc spectra to shorter wave-lengths and in particular to compare the arc and spark spectra of aluminum, zinc, and carbon. Carbon was chosen because with it an arc is easily formed; aluminum, because it furnishes a good standard line of short wave-length; and zinc, because it is rich in lines in the spark spectrum in the extreme ultra-violet and was expected to be in the arc spectrum. It was also hoped that better photographs of the spark spectra would be secured by the substitution of curved plates for the straight ones which had been previously used in this laboratory.

Since this investigation was started, Simeon[2] has published the results of his research in which he photographed the arc spectrum of carbon to λ 651, using a vacuum grating spectrograph.

APPARATUS

The vacuum chamber of the spectrograph consisted of a brass tube (large end, steel) 120 cm long and with diameters of 14 cm and 21 cm at the two ends. The ends were closed with brass plates and rubber gaskets screwed to the flanges of the tube. A window, *W*, in the large plate served for observing the arc or spark.

The concave grating was ruled with 480 lines per mm and had a radius of curvature of 83.9 cm, giving a dispersion of about 24.7 A per mm. For work with such short wave-lengths it is found desirable not to cut away all the surface of the grating, and this grating was ruled with a very light touch. This gave a very bright first-order spectrum and no observable second order.

Schumann plates on celluloid, prepared by Hilger & Company, which could be bent to the desired curvature, were used. They were $1'' \times 5\frac{1}{2}''$ and covered the whole region from the principal image

[1] *Proceedings of the Royal Society*, **95**, 248, 1919.

[2] *Proceedings of the Royal Society*, (A) **102**, 484, 1923.

to λ 3000. The plates were developed in a special hydrochinone-metol developer recommended by the manufacturers. During the development the developer was kept on ice.

The grating was mounted in the small end of the tube (see Fig. 1) and was provided with all the necessary adjustments for moving it along the tube and for rotating it about three mutually perpendicular axes. Near the other end of the spectrograph was a diaphragm which served to hold the slit and plate holder, and also to prevent stray light from the arc or spark from reaching the grating. An

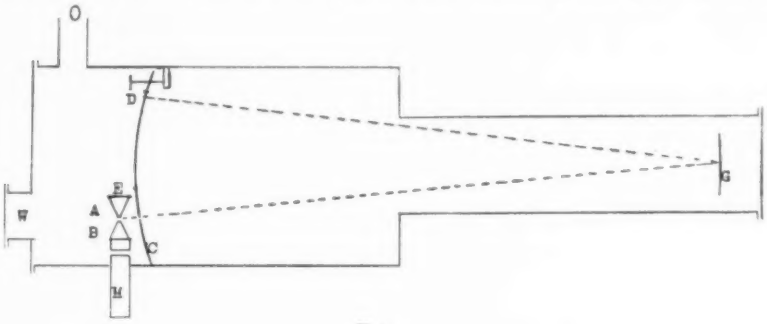


FIG. 1

auxiliary opening through the diaphragm avoided the necessity of evacuating through the slit. The plate holder *DE* formed the arc of a circle passing through the slit *S*, and both could be rotated together about a pivot at *C*, by means of a screw at *D*. The interior of the tube was painted black with a dull finish to prevent reflections.

The spectrograph was evacuated through the opening *O* which was connected to the pump by a one-inch glass tube in which were connected a liquid air trap and a mercury trap for cutting off connection between the spectrograph and pump. This trap made it possible to hold a high vacuum in the spectrograph after the pumps were stopped. A double-stage mercury diffusion pump with a Cenco Hyvac fore-pump was used for evacuation.

One of the chief difficulties encountered was in so placing the source of light that the cone of light would completely fill the grating —an essential condition for sharp lines. This was accomplished in the case of the arc by placing it very close to the slit, not more than

3 mm away. But it was necessary to keep the spark gap about three times as far away to prevent the spark from jumping to the slit and ruining it. The spark was made to pass between terminals in a vertical position which were connected to the source of high potential through large brass electrodes ground to fit bakalite insulating plugs. The same electrodes served for the arc which was used in a horizontal position.

Various attempts were made to get an arc to burn in the high vacuum maintained, but with little success until an electro-magnet and spring were arranged for striking the arc. One electrode was connected to terminal *A* which was fixed. The other was connected to *B* through a spring which held *B* against *A* when there was no current through the coil of the electromagnet *M*. An armature was attached to the terminal *B* and, when the circuit of the electromagnet was closed, *B* was drawn away from *A* and an instantaneous arc was formed.

MANIPULATION

The grating was adjusted so that the principal image fell near the end of the plate farthest from the slit. The grating and plate-holder were then adjusted to give a sharp focus at each end of the plate. Exposures to test the focus could be made in air. When the proper focus was secured, the brass plate was placed over the small end of the spectrograph and did not need to be removed so long as the grating was left in this position. The other end had to be opened after each exposure.

The arc or spark terminals were placed in position so that the cone of light filled the grating as nearly as possible, and the photographic plate was put in place. The front end-plate was then fastened on and the pumps started. Liquid air was kept on the trap to prevent mercury vapor from getting back into the spectrograph and also to freeze out any vapors present. In about an hour the pressure was usually reduced to about 0.0001 mm. The mercury trap was then closed and the apparatus allowed to stand for several hours. This served to remove the occluded gases from the walls of the tube, and also to give the plate time to dry and adjust itself to the conditions. When the pumps were again started, it was

often possible to obtain a vacuum of the order of 0.00001 mm. But as soon as an exposure was started the pressure would again increase slightly. Pressures were read on a very sensitive McLeod gauge.

Arc exposure.—The terminals *A* and *B* were connected through a rheostat to the 110-volt alternating potential with *A* and *B* separated. They were then allowed to make contact and immediately separated again by the electromagnet, forming a bright arc of very short duration. With a direct current it frequently happened that sufficient gases were liberated to make the arc continuous for a few seconds, especially in the case of the carbon arc, but this caused fogging of the plates and the alternating current was generally used. Even with it quite a little gas was liberated and time had to be allowed between arcs for the pumps to remove the gases liberated. In the early stage of the exposure it was necessary to allow ten or fifteen seconds between arcs, but after a number of contacts had been made, less gas was liberated and the contacts could be made much more frequently. In general the frequency of the contacts was regulated so as to keep the pressure about 0.0001 mm, but frequently it increased to about 0.0005 mm or more. During the major part of the exposure, contacts were made at the rate of about one per second, but instead of being made at regular intervals, eight or ten were made in rapid succession because this heated the terminals up more and gave a more intense light. A mechanical interrupter was sometimes used, but never gave as good results as when the contacts were made by hand while the operator watched the color of the terminals.

The carbon arc was the least troublesome for several reasons. There was no difficulty in getting the arc to strike. It could be heated hotter without danger of melting. And the contact points did not stick. In the case of metallic terminals, it was necessary to be constantly on guard lest they fuse together until they could not be separated, or even melt off completely. Quite often it was necessary to open the spectrograph to remedy one of these causes, and then a new plate had to be inserted and the whole process of evacuation repeated. There was also difficulty in getting the arc to strike between metals, but if they were brightly polished just before being put in, and if the arc was not made to pass between

them until all the air had been removed so that oxidation of the surface was avoided, the arc could usually be struck without difficulty. The method of exposure had to be varied continually, and it was difficult to compare the times of two exposures. In general an exposure required from fifteen to thirty minutes, depending on the width of the slit, current, etc., but occasionally good plates were secured in two or three minutes. On account of the short duration of the arc the potential and current strength could not be determined accurately. The potential drop across the arc was probably considerably below 100 volts, and the current strength from three to five amperes. Exposures longer than thirty minutes did not help much, for with a fine slit the deposit from the arc usually completely or nearly closed it in that time. The slit had to be cleaned after each exposure.

Spark exposure.—The "hot spark in vacuo" described by Millikan and Sawyer,[1] and previously used in this laboratory for spark spectra in the extreme ultra-violet, was used in this investigation. The high potential was secured from an induction coil operated as a transformer, the primary of which was connected to the 110-volt alternating potential through a variable rheostat. An auxiliary spark gap in series with the spark gap in vacuo, and a large plate condenser in parallel with the spark gaps, served to produce an intense disruptive discharge. The potential was equivalent to that required for a spark of four or five centimeters in air. A motor-driven contact-maker closed the primary and produced a series of sparks about three times per minute. From two to five hours were required for an exposure. Longer exposures could not be made on account of the variation in the length of the plate during exposure, producing either double lines or broad, hazy ones. This method of exposure required much less attention than the arc, but required a much longer time and the lines were not so sharp.

CALCULATION OF WAVE-LENGTHS

When light of any wave-length from slit S strikes the grating G at an angle i, it forms an image of the slit at a point P such that the angle $NGP = i$. P is called the principal image. The wave-

[1] *Physical Review*, **12**, 168, 1918.

length corresponding to any bright line, say at A, may be measured in terms of its distance d from the principal image.

Let us designate the angles NGA and AGP by θ and α, the wave-lengths corresponding to A and N by λ and λ_n, the grating space by σ, and the radius of curvature by R. GN is the normal. Now the concave grating formula for the first order is:

$$\lambda=\sigma(\sin i-\sin\theta) \tag{1}$$

or

$$\lambda=\lambda_n-\sigma\sin\theta \tag{2}$$

When θ is small, $\sin\theta$ is approximately equal to θ and $(\lambda-\lambda_n)$ is proportional to θ, but in the present measurements θ is too large to

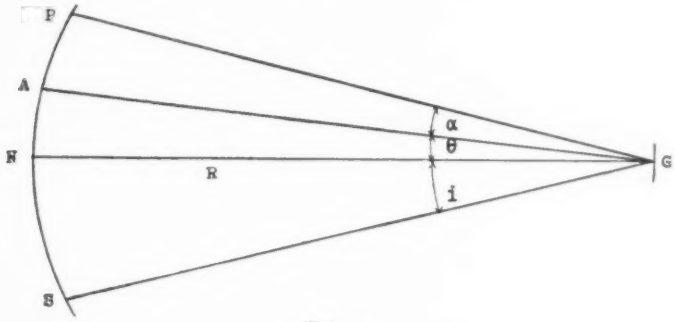


FIG. 2

make this assumption. Hence it was necessary to plot a correction curve. The correction to be applied to wave-lengths calculated on the assumption of the above proportionality is found as follows:

Expanding $\sin i$ and $\sin\theta$ and substituting in (1) we get

$$\frac{\lambda}{\sigma}=(i-\theta)\cdot\left(\frac{i^3-\theta^3}{3!}-\frac{i^5-\theta^5}{5!}\right). \tag{3}$$

Taking out $(i-\theta)$ as a factor and substituting $\theta=i-\alpha$, equation (3) reduces to

$$\lambda=\alpha\sigma\left(1-\frac{3i^2-3i\alpha+\alpha^2}{6}+\ \ldots\ .\right). \tag{4}$$

The terms omitted are of the fourth and higher degrees in i and α, and are negligible. This may also be written in the form

$$\lambda=\alpha\sigma(1-b) \tag{5}$$

where

$$b=\tfrac{1}{6}(3i^2-3ia+a^2). \tag{6}$$

Now the correction b is a function of a and therefore of λ. If b_1 is the correction in the case of some line λ_1 taken as a standard

$$\frac{\lambda}{\lambda_1}=\frac{a}{a_1}\frac{1-b}{1-b_1}=\frac{d}{d_1}\frac{1-b}{1-b_1}$$

or

$$\lambda=d\cdot\frac{\lambda_1}{d_1}\left(1+\frac{b_1-b}{1-b_1}\right)=\lambda'+C \tag{7}$$

where

$$\lambda'=d\cdot\frac{\lambda_1}{d_1} \tag{8}$$

and

$$C=\lambda'\cdot\frac{b_1-b}{1-b_1}.$$

But since b_1 is negligible in comparison with unity, as will be seen presently, the last expression reduces to

$$C=\lambda_1(b_1-b). \tag{9}$$

From (5) and (7)

$$a=\frac{\lambda}{\sigma(1-b_1)}, \qquad \text{and} \qquad \lambda=\lambda'\left(\frac{1-b}{1-b_1}\right).$$

Hence,

$$a=\frac{\lambda'}{\sigma}(1-b_1)^{-1}$$

Again we may neglect b_1 in comparison with unity and we get

$$a=\lambda'/\sigma, \qquad \text{and} \qquad i=\lambda'_n/\sigma. \tag{10}$$

Substituting these values in (6) we now get

$$b=\frac{1}{6\sigma^2}(3\lambda'^2_n-3\lambda'_n\lambda'+\lambda'^2) \tag{11}$$

and

$$C=(b_1-b)=\frac{\lambda'}{6\sigma^2}[(\lambda_1^2-\lambda'^2)-3\lambda'_n(\lambda_1-\lambda')]. \tag{12}$$

This gives the correction C as a function of the grating constant, the standard wave-length, the wave-length at the normal, and the

unknown wave-length. λ_n was kept at approximately 2000 A most of the time and was known with sufficient accuracy for this correction. The correction is zero at the principal image and at the standard line, negative between them, and positive for all values of λ greater than λ_1. C was plotted against λ' for several standard lines and by interpolation the correction, corresponding to any λ measured in terms of any standard line in the neighborhood of

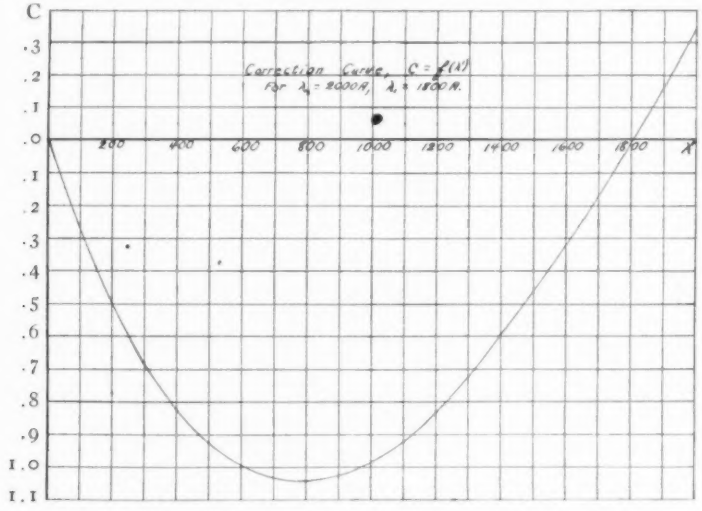


FIG. 3

2000 A, could be read to .01 A. The magnitude of the correction involved may be seen from the accompanying correction curve for $\lambda_1 = 1800$ and $\lambda_n = 2000$.

The plates were measured on a Gaertner 8-cm comparator. Since the distance d_1 involved in equation (8) was about 8 cm, it was very necessary that the screw have a constant pitch throughout the whole distance. This was found not to be true, and a calibration curve was plotted for it in terms of a standard decimeter, certified by the Bureau of Standards. The use of lines of longer wave-length than λ 2150 as standards was impossible because they were more than 8 cm from the principal image.

On account of the variation of the length of the plate with humidity and temperature, especially the former, the dispersion

constant (λ_1/d_1) could not be assumed the same for all plates, or even for the same plate on different days. At first considerable difficulty was encountered in the variation of the length of the plate during the measurement of it. For if a setting was made on the principal image, then on a line to be measured, and finally on the standard line, and if the plate contracted between the second and third readings, equation (8) would give too large a value for λ', but if the readings were taken in the reverse order, it would give too small a value. This was found to be the case if readings were taken immediately after the plate was adjusted on the comparator, but after it was left for about thirty minutes a condition of equilibrium was reached, and readings thereafter in both orders were quite consistent. To still further lessen the error due to contraction, which might occur during the measurement of all the lines on a plate, certain sharp lines which were found in both the arc and spark spectra were measured many times on each of several plates and their wave-lengths served as secondary standards for correcting the wave-lengths of other lines on each plate.

There were no carbon lines within 8 cm of the principal image which could be used as standards, but certain very prominent lines occurred in the spectra of both aluminum and carbon. These were measured in terms of the aluminum line at λ 1862.70, and were used as standards in measuring the other carbon lines. These measurements were then checked in two distinct ways: (1) using carbon as one electrode and aluminum as the other, plates were secured giving the standard aluminum line and most of the carbon lines, which could then be measured directly; (2) by resetting the plate during a series of measurements the carbon line at λ 2297.60 could be used as a standard. This second check was of least value because it meant handling the plate and a consequent change in length.

The standards for zinc were taken from Paschen's measurements[1] which were reduced from the Rowland System to the International by the correction curve given by Kayser,[2] and then to vacuum by the Bureau of Standards' reduction tables.[3]

[1] Kayser, *Handbuch der Spectroscopie*, **6**, 860. [2] *Ibid.*, p. 890.

[3] *Bureau of Standards Bulletin*, **14**, 731, 1919.

Wherever more than one standard line was available on a plate, all were used in determining the dispersion constant to avoid errors due to the peculiarities which might exist in any one line.

RESULTS

Tables I, II, and III give the wave-lengths in International units of the arc and spark spectra of aluminum, zinc, and carbon. The arc lines were sharp in every case and the spark lines of carbon and

TABLE I

ALUMINUM

λ	Intensity		λ	Intensity		λ	Intensity	
	Arc	Spark		Arc	Spark		Arc	Spark
678.0	.....	5	1328.7	.....	2	1622.6	.....	3
696.2	2	.....	1334.8	7†	3	1629.2	.....	4
718.9	3	.....	1336.2		3	1639.4	.....	4
833.5	6†	2	1343.8	.....	1	1644.9	.....	4
834.9		2	1353.3	0	.....	1651.9	.....	2
881.2	.....	2	1360.0	.....	2	1670.9	10	4
904.5	5	4	1380.0	5	1	1673.2	.....	4
977.4	3	4	1384.5	6	3	1688.7	.....	2
1010.7	2	0	1437.4	1	.....	1706.9	.....	1
1037.2	4	2	1456.7	.....	1	1719.5	6	0
1110.4	1	.....	1464.3	.....	0	1721.3	6	0
1113.5	1	.....	1473.6	.....	3	1725.0	8	1
1152.3	1	.....	1486.2	.....	1	1728.5	0	.....
1176.0	2	4	1491.1	.....	1	1749.0	2	.....
1190.1	4	.....	1499.8	.....	3†	1749.7	.....	2
1192.1	4	.....	1506.0	.....	2	1760.0	5	.....
1206.9	6	.....	1515.8	.....	2	1761.8	4	.....
1215.9	6	4	1540.1	3	.....	1763.8	5	1
1253.6	.....	0	1548.5	.....	2‡	1764.4	4	.....
1260.9	0	.....	1552.6	.....	3	1767.6	5	0
1262.8	.....	0	1560.7	.....	1	1777.2	1	.....
1265.2	1	.....	1561.3	1	.....	1808.1	0	.....
1266.1	.....	0	1562.4	.....	0	1818.8	0§	.....
1292.4	.....	2	1581.7	.....	6	1854.7	10	8
1299.6	0	.....	1598.6	.....	2	1858.0	4	.....
1302.4	1	.....	1601.0	.....	2	1862.70*	10	8
1305.5	0	.....	1605.8	8	1	1930.99*	6	.....
1307.4	.....	1†	1611.9	8	3	1935.87*	6	2
1319.3	.....	1	1619.7	.....	3	1990.49*	8	1

* Used as standards.
† Broad.
‡ Probably double.
§ Possibly not a line.

aluminum were good, but the zinc spark lines were always hazy and in certain portions of the plate there was so much continuous background and the lines were so close together that measuring was very difficult. There was some disagreement in the wave-

lengths calculated from measurements on different plates, but when the averages for several plates and for at least four measurements of each plate were taken, the agreement between the wave-lengths

TABLE II

CARBON

λ	Intensity		λ	Intensity		λ	Intensity	
	Arc	Spark		Arc	Spark		Arc	Spark
460.1	.....	1	1077.0	.....	0	1374.8	0	3†
539.8	.....	2	1085.9	.....	1†	1432.3	1†	2
544.0	.....	0	1093.3	.....	1	1463.7	2	3
550.1	.....	0	1139.8	0	3	1482.2	1	1
562.0	.....	1	1142.3	1	5	1548.5	.....	3
565.2	.....	1	1146.4	0	.....	1551.1	.....	3
574.9	.....	2	1176.0	8	8	1561.2	10	6
595.5	1	5	1190.1	1†	2†	1599.9	.....	1
600.9	.....	0	1194.1	2†	2†	1613.6	1	3
636.8	.....	2	1206.9	.....	1	1619.8	.....	1
642.3	.....	4	1215.9	3	5	1624.1	.....	0
651.9	2	6	1230.7	.....	0	1657.4	10	6
687.1	6	8	1247.9	.....	5	1716.8	1†	4
699.3	.....	0	1261.8	5	4†	1721.7	.....	3
704.6	.....	0	1265.2	.....	0§	1752.1	1	1
711.6	.....	0	1268.6	.....	0§	1760.7	2	4
800.2	0	4	1272.9	.....	0§	1808.1	10	7†
807.1	6	6	1277.9	5	4†	1891.1	.....	0§
810.2	0	3	1280.9	4	3†	1892.7	.....	0§
858.9	8	7	1284.2	.....	2†	1930.8	8	6
904.5	10†	8	1303.1	.....	3	1954.1	2	5
946.1	1	2	1321.8	.....	0§	2020.2	4†	4†
977.4	6	8	1324.3	6	5	2072.5	5	4†
1010.7	8	7	1327.3	.....	0§	2074.2	5	
1037.2	10	8	1329.7	6	4	2131.9	1	3
1064.0	.....	0	1335.5	10†	8†	2297.60	2	5
1066.5	3	5	1362.8	1	2			

† Broad. § Possibly not a line.

for the arc and the spark were such that there was no justification for publishing the wave-lengths separately. But the relative intensities varied considerably. It is believed that the wave-lengths given are in most cases accurate to within one- or two-tenths of an angstrom, except in the case of hazy zinc lines.

The present investigation does not represent any extension of the spark spectrum over that of Millikan, Sawyer, and Bowen, but it is hoped that, by the use of curved plates, sharper lines may have been secured and more accurate measurements made. So far as the author is aware, no other investigator has secured the arc spectra for metals below λ 1376. The present investigation

TABLE III

Zinc

λ	Intensity		λ	Intensity		λ	Intensity	
	Arc	Spark		Arc	Spark		Arc	Spark
467.5	.....	0	1204.5	1	2	1420.6	3	2‖
473.0	.....	1	1212.9	.....	1	1426.0	.....	2‖†
479.1	.....	1†	1216.2	.....	1	1430.7	.....	1
568.5	.....	0§	1223.7	.....	4	1432.5	.....	2
573.2	.....	0	1229.0	.....	3	1434.8	.....	0§
577.9	.....	0	1234.4	.....	0	1439.5	4	1
583.5	.....	0	1240.2	.....	0‖	1443.0	.....	2
678.6	.....	5‡	1243.7	.....	0	1445.6	5	4
714.5	.....	2‡	1250.5	.....	1	1451.3	5	4
756.0	.....	0	1253.9	.....	4	1457.4	4	4
768.1	0	1	1263.1	.....	4	1460.3	.....	1
780.4	0	1‖	1266.1	.....	3	1464.4	.....	3
786.6	.....	0§	1268.8	.....	3	1466.3	.....	1
825.4	.....	1‖	1273.4	.....	1	1473.7	.....	5
830.4	.....	0‖	1278.3	1	0	1477.5	4	1‖†
848.6	.....	0§	1280.8	.....	1§	1478.7	3	
853.0	.....	1‖	1284.5	.....	1	1486.6	6	3
881.9	2	4‡	1292.8	.....	3‖†	1491.2	.....	3
889.5	1	2	1295.7	.....	3‖†	1493.6	1	.....
893.6	0	0	1297.3	.....	0	1499.8	.....	5†
898.0	.....	0	1301.6	.....	1‖	1506.2	.....	5
900.8	0	.....	1304.4	.....	1‖	1510.8	2	.....
946.0	.....	0§	1307.1	.....	2	1516.1	0	5
950.1	.....	0‖†	1319.3	.....	2‖†	1524.4	4	.....
954.5	.....	0§	1319.6	.....	1	1528.2	0§	.....
958.6	.....	1†	1322.2	.....	2‖†	1534.4	2	.....
968.0	.....	0	1324.2	.....	0§	1535.4	2	.....
973.5	.....	1‖	1327.3	.....	0§	1541.8	0§	.....
977.7	.....	2‖	1328.7	.....	2‖†	1547.6	0†	.....
991.6	.....	1‖	1336.0	0§	.....	1552.7	0	5
1001.9	.....	1‖	1340.0	.....	1‖	1556.6	0	.....
1008.0	.....	2‖	1344.0	.....	2‖	1561.3	0	4‡
1010.7	.....	2‖	1349.3	.....	1	1573.7	0	.....
1018.4	.....	2‖	1353.0	.....	1	1581.9	4	6
1029.9	.....	2‖	1360.2	.....	2	1590.0	6	.....
1037.4	.....	2‖	1362.9	.....	1	1595.9	0	.....
1049.8	.....	3	1364.6	.....	1	1598.5	.....	4
1133.6	.....	1‖	1366.0	.....	1	1601.1	.....	4
1136.0	.....	1‖	1374.8	.....	2‖	1619.8	0	5
1145.5	.....	2	1378.0	.....	2‖	1622.8	0	5
1155.9	.....	2‖	1387.8	.....	3	1629.3	2	6
1166.2	.....	2‖	1388.8	.....	1	1639.6	1	6
1170.6	.....	1‖	1395.7	4	3	1645.2	1	6
1176.0	.....	3‖†	1402.0	.....	2	1652.1	1	4
1179.8	.....	1‖	1406.6	.....	2	1671.9	4	7
1182.4	.....	1‖	1409.1	.....	1	1673.2	3	
1195.8	.....	2	1411.6	.....	1	1682.5	6	.....
1200.7	.....	2‖	1414.4	.....	0	1688.7	.....	4

* Used as standards.
‖ Hazy.
† Broad.
‡ Probably double.
§ Possibly not a line.

TABLE III—*Continued*

λ	Intensity		λ	Intensity		λ	Intensity	
	Arc	Spark		Arc	Spark		Arc	Spark
1695.3	.....	2	1844.7	.....	1‖	2058.4	4	.....
1706.6	.....	4	1856.7	.....	1‖	2062.58*	9	10
1727.1	2	.....	1864.6	.....	1‖†	2064.9	5	3
1749.7	.....	4	1871.8	.....	1	2067.1	2	.....
1753.7	.....	2	1874.3	.....	1	2070.4	1†	.....
1762.2	.....	2‖	1877.9	.....	1	2079.8	4	1‖
1768.5	.....	4	1881.8	.....	1	2087.7	4†	1‖
1777.4	.....	1	1907.3	.....	1	2096.4	2	.....
1797.0	3	.....	1919.3	0	2	2097.7	2	.....
1808.4	.....	0‖	1929.2	1	.....	2100.55*	8	8
1811.3	.....	1‖	1942.2	.....	1	2102.9	4	4
1814.2	.....	0§	1946.0	.....	1	2105.1	4	.....
1816.5	.....	0‖	1954.4	.....	1§	2134.9	1	.....
1825.3	7	1‖	1969.5	.....	1	2139.29*	8	8
1825.4	.....	1‖	1982.0	.....	1§	2145.14*	4	4
1833.7	1	1	2026.16*	10	10			
1839.1	.....	2	2054.2	0	.....			

demonstrates the practicability of the vacuum arc spectrograph for metals to about λ 600, and it is believed that it can be extended even farther. Its advantages over the spark are: (1) That it gives sharper lines; and (2) that it requires less time for an exposure. The method can be extended to find the spectra of salts by using a vertical arc and cored carbons. The carbon arc was used first because it is the most easily operated. Then, too, it was desired to know the carbon spectrum so that carbon could be used as one terminal in securing the spectra of other substances By this arrangement the sticking of the terminals does not cause so much trouble. But for the purpose of identifying lines at least one exposure was made for each metal, using both terminals of the same metal.

On account of the variation of the length of the celluloid plates with moisture conditions, glass is much to be preferred if it can be bent to the proper curvature. However, when compared with straight glass plates, the advantage derived from a sharp focus more than offsets the disadvantage of the variable length.

In conclusion the author wishes to acknowledge his indebtedness to Professor H. G. Gale, Dr. A. J. Dempster, and Dr. H. B. Lemon for helpful suggestions.

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AN INTERCOMPARISON OF TEMPERATURE SCALES

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ABSTRACT

List of laboratories of which comparison was made.—This paper deals with a comparison of the high-temperature scales in use at the Bureau of Standards, the General Electric Company's Research Laboratories at Schenectady, the Physical Laboratory at the University of Wisconsin, the National Physical Laboratory of England, and the Nela Research Laboratory at Cleveland.

Method of comparison.—Several tungsten lamps that had been carefully aged and calibrated were sent to each of the foregoing laboratories and the temperatures of the lamps were measured for specified currents with a disappearing filament optical pyrometer using a plate of red glass as the monochromatic screen. The reductions necessary to make the readings comparable because a non-black body was used are pointed out.

Results of the comparison are given in Table II. The agreement found is very good, the maximum difference being only a few degrees for any point of the entire range from 1400° K to 2700° K.

In all radiation work general agreement upon a uniform standard of high temperatures is of the first importance and next in order is the standardization of some short and convenient method for accurate temperature measurements. The present paper deals with the intercomparison of the high-temperature standards now used in several research laboratories in this country and abroad by the method of brightness temperatures as measured by the disappearing filament optical pyrometer.

Day[1] and his co-workers of the Geophysical Laboratory some ten years ago did some very laborious, accurate, and important work in extending earlier temperature measurements with the constant volume nitrogen thermometer up to the melting-point of palladium. In this work the temperatures of several of the standard melting-points were determined on the gas thermometer scale. Buckingham[2] has calculated the corrections to be applied to temperatures measured on the constant volume nitrogen scale to reduce them to the absolute scale. These corrections are given directly to temperatures of about 1500° K and by extrapolation can be

[1] *American Journal of Science*, **26**, 405, 1905.

[2] *Bulletin of Bureau of Standards*, **3**, 237.

extended to the palladium point. According to Buckingham's extrapolated values the correction to be applied to Day and Sosman's value for the melting-point of palladium is about 0°.6 C. The two points investigated by Day and Sosman most used for reference in the field of high-temperature radiation are the gold point and the palladium point. Practically all the work that has been done in the high-temperature region has been based upon one or the other of these values, i.e., gold point, 1336° K, or palladium point 1823° K.

Some work done with the disappearing filament pyrometer in the Nela Research Laboratory[1] and at the Reichsanstalt[2] showed a possible error in the melting-point of palladium when compared with the foregoing value for the melting-point of gold. This later data has been obtained by measurements on the relative brightness for a particular wave-length interval of the black body at the gold point and at the palladium point. From the ratio thus determined and Wien's equation c_2 taken as 14350 μ deg., a value of 1828° K is found for the palladium point in terms of 1336° K for the gold point. This is but 5° higher than the value set by Day and Sosman and is almost within their assigned limit of error.

Almost all of the temperature measurements above the melting-point of gold, or at most above 200° or 300° higher than this temperature, are determined by means of an optical pyrometer calibrated from a black body held at one or more standard temperatures.

The accuracy of the determinations in this high-temperature region depends upon two things: first, upon how well the black-body conditions have been reproduced, and second upon the accuracy with which the standard melting-points have been determined. When gold or palladium is used as the standard metal, the error due to impurities may in general be neglected if high purity samples are obtained from Heraeus or the mint. If the temperature scale is extrapolated above that of the standard temperature, i.e., gold or palladium point, by the use of an absorbing screen or a sector disk in terms of one of the radiation laws, there is a possibility of a third source of error. This last error may be caused by

[1] *Astrophysical Journal*, **42**, 300, 1915.

[2] *Zeitschrift für Instrumentenkunde*, **33**, 95, 1913.

an error in the transmission of the sector or absorbing glass, by the improper location of the sector,[1] or by an error in wave-length[2] used, if a colored glass is used as the monochromatic screen. These three sources of error may lead to very great uncertainties in the final results.

The sources of error just mentioned apply to measurements on a black body. If the temperature of a non-black body is determined by measuring the brightness for a given wave-length λ with the pyrometer, the temperature thus obtained is called the brightness temperature of the body and is the temperature to which a black body must be raised to give the same brightness for the same wave-length. As a non-black body may have a different brightness temperature for every different wave-length examined, the brightness temprature of a hot body is indefinite unless the wave-length employed in the measurement is specified. Thus if we say the brightness temperature of a body is 1500° K for $\lambda = 0.665\ \mu$, we mean that for this wave-length the body has the same brightness as a black body at 1500° K for this same wave-length.

To discover the extent of agreement among the high temperature scales in use by a number of research laboratories at home and abroad, several tungsten lamps that had been carefully aged and then calibrated in the Nela Research Laboratory were sent to different laboratories with the request that the temperature of the lamps be measured for specified currents and returned to this laboratory. This intercomparison has been made possible by the kind cooperation of Dr. Stratton, director of the Bureau of Standards, Sir J. E. Peteval, director of the National Physical Laboratory of Great Britain, Dr. C. E. Mendenhall, of the University of Wisconsin, and Dr. Langmuir, of the Research Laboratory of the General Electric Company. In each of the laboratories the temperatures were measured with a disappearing filament optical pyrometer using a plate of red glass as the monochromatic screen.[3]

[1] *Journal of the Optical Society*, **4**, 317, 1920.

[2] *Astrophysical Journal*, **42**, 294, 1915.

[3] The optical pyrometer can be used to measure the apparent brightness or brightness temperatures of the planets (*Nature*, **8**, 533, 1923) for different parts of the visible spectrum by the use of suitable color glass screens.

Although this intercomparison has been carried out by measurements on tungsten filaments, the results give not only a comparison of the brightness temperature of tungsten but also a valid comparison of the high-temperature scale. As was mentioned above, when we say that a non-black body has a particular brightness temperature for a definite wave-length interval, we mean that it has the same brightness for this wave-length interval as the black body for the same temperature. If strictly monochromatic radiations were used there would be no question about the comparison. By considering the "effective wave-length" of a color glass having a wide transmission band, as will appear later, the results obtained are just as definite as they would be if a screen were used that had a very narrow transmission band. Thus the tungsten filament is used as a convenient source with which to compare the temperature of the different standard black bodies.

In Figure 1 is shown a picture of one of each type of lamp used in the intercomparison and in Table I a description of the different individual lamps is given.

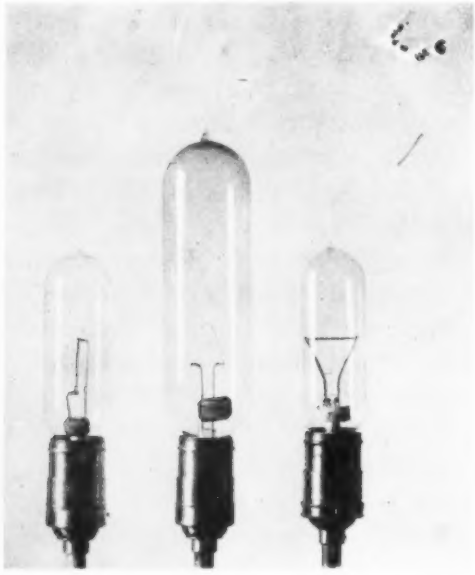
The exact point at which the temperature of each of the ribbon lamps was to be measured was indicated either by a pointer, a notch in the supporting lead, or a small notch in the ribbon itself. The wire filament of the lamp T-30-C was in the form of a hairpin loop with a rather sharp bend. The temperature of this filament was measured at the center of the loop.

Different practices have been followed at the different laboratories in establishing high-temperature scales. The Bureau of Standards bases its high-temperature scale on the melting-point of gold (1336° K) and extrapolation by means of Wien's[1] equation using for c_2 14350 μ deg.[2] At the National Physical Laboratory the high-temperature scale is based on the melting-point of palladium taken as 1828° K and extrapolation made by Wien's equation using 14350 μ deg. for c_2. At the physical laboratory of the University of Wisconsin high-temperature measurement is based upon

[1] Wien's equation has been used here rather than Planck's because of greater convenience in computation. Both laws give practically the same energy distribution in the visible spectrum for temperatures below 3000° K.

[2] Since this intercomparison was made the Bureau of Standards have decided to use 14330 μ deg. for c_2.

the melting-point of palladium taken as 1822° K. The scale is extrapolated by Wien's equation with c_2 as 14350 μ deg. At the Research Laboratory at Schenectady the high-temperature scale is



1 2 3

FIG. 1.—Picture of one of each of the different types of lamps used in the intercomparison. Numbers 1 and 3 have ribbon filaments; number 2 has a 20-mil. (0.5 mm) diameter wire filament.

TABLE I

DESCRIPTION OF THE LAMPS USED IN THE INTERCOMPARISON

Lamp No.	Kind of Filament
T-25-C	Horizontal ribbon, 2½ mm wide, gas-filled
T-16-B	Vertical ribbon, 2½ mm wide, vacuum
T-30-C	Wire, 20 mil. (0.5 mm) diameter—gas-filled
T-17-C	Horizontal ribbon, 3 mm wide, gas-filled
T-18-B	Vertical ribbon, 2½ mm wide, vacuum
T-77-B	Same as T-16-B
T-78-C	Same as T-30-C

based on the melting-point of gold (1336° K) and the scale extrapolated by Wien's equation with c_2 as 14350 μ deg. At Nela Research Laboratory the high-temperature scale is based upon the melting-point of gold (1336° K) and the scale extrapolated by Wien's

equation with c_2 taken as 14350 μ deg. For convenience in calibration of optical pyrometers the melting-point of palladium is used as the point of reference. Using the best Heraeus palladium obtainable, the value of this point in terms of the scale employed has been found to be 1828° K.

For a strict intercomparison of the results obtained in the different laboratories certain factors must be taken into account to reduce all measurements to the same basis. The common basis assumed for this purpose is the one adopted by the General Electric Company for use in its laboratories. This temperature scale is based upon the assumption of Wien's equation with c_2 taken as 14350 μ deg. and upon the melting-point of gold taken as 1336° K, i.e., degrees Centigrade+273 degrees. On this scale the melting-point of palladium is 1828° K. For convenience in calibration of optical pyrometers, a black body held at the melting-point of palladium is used as a point of reference.

As it was found that the red glasses used as monochromatic screens in the various laboratories did not have the same spectral transmission, the brightness temperatures obtained were not all to be ascribed to the same wave-length. If the brightness temperature of a particular source is measured with an optical pyrometer using a colored glass having a wide transmission band as a monochromatic screen, there has been some question as to just what wave-length this brightness temperature is to be ascribed. The "effective wave-length" of a monochromatic screen has been defined[1] as the wave-length such that for any definite temperature interval for a black body the ratio of the radiation intensities for this wave-length shall equal the ratio of the integral luminosities through the screen used.

The color temperature of a particular source has been defined as the temperature of a black body which has the same distribution of energy in the visible spectrum as the source under consideration. It has been found experimentally that most metals when heated radiate in such a manner that they can be color matched against a black body. These color matches are very easily and accurately made with an ordinary contrast photometer. It is to be noted

[1] *Astrophysical Journal*, **42**, 295, 1915.

that, when two bodies have the same color temperature, it is not necessary that they shall have the same brightness for any particular wave-length interval.

From a consideration of the effective wave-length and the color temperature, it has been shown[1] that the brightness temperature, obtained with a colored glass having a wide transmission band as the monochromatic screen, is to be ascribed to the effective wave-length of the monochromatic screen for the temperature interval between the brightness temperature obtained and the corresponding color temperature of the source being studied.

First, the reduction due to a difference in the standard temperature will be considered. If a temperature T_2 is obtained by extrapolation by means of Wien's equation from a standard temperature T_1 the following is the relation between the value of T_2 and another T_2' obtained from another T_1' of the standard temperature:

$$1/T_2 - 1/T_1 = 1/T_2' - 1/T_1' \tag{1}$$

The second reduction is made necessary by the use of a different value of the constant c_2. If different values of c_2 are used in extrapolating temperatures from a standard temperature T_1 by means of Wien's equation the following is the relation between the two c_2's and the resulting temperature:

$$c_2(1/T_1 - 1/T_2) = c_2'(1/T_1 - 1/T_2') \tag{2}$$

The third reduction was to bring the various brightness temperatures reported to the same wave-length. From the conditions that hold at color match and Wien's equation the following relation can be shown to hold between two brightness temperatures (S_1 and S_2) and the wave-length (λ_1 and λ_2) to which they correspond:

$$1/S_2 = \lambda_2/\lambda_1(1/S_1 - 1/T_c) + 1/T_c \tag{3}$$

where T_c is the color temperature corresponding to the brightness temperature S.

By means of the three relations just given the different temperatures reported have all been reduced to a common basis and are given in Table II. From the values given it can be seen that the

[1] *General Electric Review*, **120**, 752, 1917; *Trans. Faraday Soc.*, **15**, 21, 1920.

agreement is very good. The variation in the brightness temperatures of lamp T-25-C between the two measurements in this Laboratory is 2°, which is the same as the maximum difference between

TABLE II

RESULTS OF INTERCOMPARISON OF TEMPERATURE SCALES

$c_2 = 14350\ \mu$ deg.: $\lambda = 0.665\ \mu$: melting-point of Au = 1330° K (pd. = 1828° K).

Lamp	Current	N.R.L. Oct. 1916	G.E. Lab. Schenectady	N.R.L. Nov. 1916	Bureau of Standards	N.R.L. April 1917
T-25-C	10.9	1826° K	1828° K	1826° K	.....	.....
	14.6	2214	2214	2215	.....	.....
	18.0	2518	2518	2516	.....	.....
T-16-B	5.3	.....	.....	1429	1431° K	1427° K
	6.8	1618	1613	1617	1619	1614
	8.6	1816	1811	1811	1813	1812
	11.8	2128	2116	2122	2122	2121
T-30-C	15.3	1813	1813	1813	1814	1813
	21.0	.....	2307	2304	2302	2303
	27.5	2756	2752	2752	2762	2752

Lamp	Current	N.R.L. March 1916	University of Wisconsin C.E.M.		University of Wisconsin G.R.G.	N.R.L. July 1917
T-17-C	11.0	1810	1813	.....	1816	1810
	14.6	2193	2197	.....	2202	2196
	18.0	2499	2506	.....	2516	2497
T-18-B	6.7	1599	1602	.....	1605	1597
	8.8	1806	1816	.....	1819	1807
	12.0	2105	2119	.....	2123	2107

Lamp	Current	N.R.L. April 1920	N.P.L. April 1922	N.R.L. June 1922	Bureau of Standards Jan. 1923	N.R.L. Jan. 1923
T-77-B	5.2	1410° K	1403	1406	1401	1401
	6.7	1599	1596	1595	1596	1591
	8.5	1796	1794	1794	1792	1791
	11.7	2106	2106	2104	2105	2104
T-78-C	15.4	1825	1825	1826	1824	1828
	20.4	2262	2265	2266	2265	2269
	27.4	2746	2757	2753	2755	2755

the values of this Laboratory and the Research Laboratory at Schenectady. The agreement for T-16-B is about the same between the first two measurements in this Laboratory and between this Laboratory and Schenectady. The lamp apparently held much

more constant during its trip to the Bureau of Standards, and here the agreement is even better. The results given by T-30-C are all that can reasonably be expected in the circumstances. The agreement of the results shown in the second part of the table on the two lamps sent to the University of Wisconsin is not so good as that of the results obtained by the other two laboratories. The lamps held very constant, as shown by the two measurements made in Nela Research Laboratory.

Three lamps were sent to the National Physical Laboratory, but unfortunately one of them was broken in transit. After the remaining two lamps had been measured again in the Nela Research Laboratory the Bureau of Standards made a measurement on the temperature of these lamps. The results of this part of the intercomparison are given in the third part of Table II.[1] The lamps were burned many hours at the National Physical Laboratory, and the measurements reported were obtained just before the lamps were returned. For this reason but little weight is to be given to the earlier values obtained in this laboratory.

From the data given in the table it appears that the characteristics of both lamps were slowly changing. However, the agreement is a very satisfactory one.

It is gratifying to know that the high-temperature scales in use in different laboratories in this country show so small a divergence and that this scale and the one used at the National Physical Laboratory of Great Britain are in such close agreement over the important range between 1400° K to 2750° K.

It is expected that this intercomparison will be carried farther and results obtained from more of the industrial laboratories of this country and elsewhere.

Nela Research Laboratory,
National Lamp Works
Cleveland, Ohio
August 1923

[1] *Report of the National Physical Laboratory*, p. 54, 1922.

NOTE ON THE FORMULATION OF ABSORPTION BANDS IN THE NEAR INFRA-RED

By W. F. COLBY

ABSTRACT

The two well-known absorption bands of *HCl* have been reformulated with half-parameter numbers. From these formulae the combination band corresponding to a vibrational quantum change $1 \rightarrow 2$ is calculated and found to be in agreement with the faint absorption band recently observed.

In a recent number of this *Journal*[1] the writer was joint author in a report on a new faint absorption band of hydrogen chloride which lies in the same region as the well-known fundamental band with center at $3.4\ \mu$. The new band appeared only when the absorbing gas was heated to 300° C. It had all the characteristics of the band predicted by Kratzer[2] as due to a vibrational quantum spring from 1 to 2, although displaced with respect to his calculated band by an almost constant amount of about 80 units. None of the observational data which entered into the computation could have accounted for so large a discrepancy. Thanks to a suggestion of Dr. Pauli, the formulae for the strong absorption bands of hydrogen chloride are here restated with half parameter numbers and, with the help of the new molecular constants thus obtained, a much more satisfactory expression for the weak band results. Kratzer[3] has pointed out in recent papers how advantageous the half parameter numbers are in accounting for the fine structure and other line characteristics in the visible bands and in explaining the missing center in the near infra-red bands. Kramers and Pauli[4] have likewise used them successfully in a discussion of the infra-red bands. More recently Curtis[5] has used half numbers in stating the helium-band spectrum, and again Kiuti[6] in the band spectrum of hydrogen.

[1] Colby, Meyer, and Bronk, *Astrophysical Journal*, **57**, 7, 1923.

[2] A. Kratzer, *Zeitschrift für Physik*, **3**, 289, 1920.

[3] A. Kratzer, *Annalen der Physik*, **71**, 72, 1923.

[4] H. A. Kramers, *Zeitschrift für Physik*, **13**, 343, 1923. Kramers and Pauli, *ibid.*, **13**, 351, 1923.

[5] W. E. Curtis, *Proceedings of the Royal Society*, **103**, 315, 1923.

[6] Masazo Kiuti, *Proceedings of Phys.-Math. Society of Japan*, 3d Series, **5**, No. 2.

Aside from providing a more satisfactory explanation of the missing center, this restatement of the formula for the fundamental absorption band of *HCl* yields nothing new nor decisive. The original formula given for this band was of the form

$$\nu = A + Bm + Cm^2 + Dm^3.$$

A transformation $m = n + \frac{1}{2}$ yields a similar formula in n. When, however, one considers the relation of several bands through the combination principle, the choice of parameter numbers becomes very important.

With the notation of Kratzer, the energy term for these bands may be written.

$$W'''_n = W'^{\circ}_n + hB_n m^2 - h\beta_n m^4$$

or with half parameter numbers

$$W'''_n = W'^{\circ}_n + hB_n (m+\tfrac{1}{2})^2 - h\beta_n (m+\tfrac{1}{2})^4.$$

The parameter number m in former paper corresponds here to a change in rotation from

$$m-\tfrac{1}{2} \text{ to } m+\tfrac{1}{2} \text{ and in vibration from } n=n_1 \text{ to } n=n_2.$$

We have then for the frequency

$$\nu_m = \frac{W'^{\circ}_{n_2} - W'^{\circ}_{n_1}}{h} + B_{n_2}(m+\tfrac{1}{2})^2 - B_{n_1}(m-\tfrac{1}{2})^2 - \beta_{n_2}(m+\tfrac{1}{2})^4 + \beta_{n_1}(m-\tfrac{1}{2})^4,$$

or in powers of m and neglecting terms with $(\beta_{n_1} - \beta_{n_2})$

$$\nu_m = \nu_{n_1 n_2} + \frac{B_{n_2} - B_{n_1}}{4} + (B_{n_1} + B_{n_2} - \beta)m + (B_{n_2} - B_{n_1})m^2 - 4\beta m^3.$$

Comparing this notation with that used by us in previous papers.

$$B_n = \frac{h}{8\pi^2 I_o} - a_n, \qquad \beta = \frac{hu^2}{8\pi^2 I_o}.$$

For the fundamental band

$$n_1 = 0, \qquad n_2 = 1$$

and

$$\nu = \left(\nu_{01} + \frac{B_1 - B_0}{4}\right) + (B_0 + B_1 - \beta)m + (B_1 - B_0)m^2 - 4\beta m^3.$$

The four constants here involved may be determined from the empirical equation for this band, viz.,

$$\nu = 28860.7 + 205.983\, m - 3.01023\, m^2 - .0205658\, m^3$$

giving

$$\begin{aligned} \nu_{01} &= 28861.45 \\ B_1 &= \quad 101.489 \\ B_0 &= \quad 104.499 \\ \beta &= \quad\quad .00514 \end{aligned}$$

For the band at 1.7 μ,

$$n_1 = 0, \qquad n_2 = 2,$$

and

$$\nu = \left(\nu_{02} + \frac{B_2 - B_0}{4}\right) + (B_0 + B_2 - \beta)m + (B_2 - B_0)m^2 - 4\beta m^3 .$$

This band has been measured by Imes[1] but not with the same precision as the fundamental band, partly because it is so faint and partly because the wave-length determinations are complicated by the partial resolution of each line into two components due to the chlorine isotopes. The new constants B_2 and ν_{02} were nevertheless determined from these measurements. This was done most conveniently by adding wave numbers corresponding to m and $-m$. β is thus eliminated and one obtains by least squares

$$\begin{aligned} \nu_{02} &= 56671.2 \\ B_2 &= \quad 98.618 \end{aligned}$$

The weak band corresponds to a vibration change from 1 to 2 and the formula reads

$$\nu = \nu_{02} + \frac{B_2 - B_1}{4} + (B_1 + B_2 - \beta)m + (B_2 - B_1)m^2 - 4\beta m^3 .$$

This contains only constants obtained from the other bands and may be written numerically

$$\nu = 27809.1 + 200.102\, m - 2.871\, m^2 - .02056\, m^3.$$

[1] E. S. Imes, *Astrophysical Journal*, **50**, 251, 1919.

The following table shows computed and observed values.

m	ν_{comp}	obs	Diff.
− 9	25790.6	25797	6.4
−10	25541.5	25547	5.5
−11	25287.9	25288	0.1
−12	25030.0	25021	−9.0
−13	24767.7	24760	−7.7

The precision of measurement of the faint band is by no means so great as in the case of the other bands and the probable error may in the weakest lines be nearly as great as the deviations here indicated. In addition to this, however, comes the uncertainty in the two constants determined from the band at 1.7 μ, which may account for the apparently systematic error.

In addition to the above computation we have another test in the determination of the constant u which was used in our former paper and which now enters in the new constant

$$\beta=\left(\frac{hu^2}{8\pi^2 I_0}\right).$$

A direct computation of this constant from the constants of the fundamental yields

$$u=0.00701.$$

If, however, one makes use of a relation, developed by Kratzer in his earlier paper, which involves also the band at 1.7 μ, viz.,

$$\frac{W_2^\circ}{h}=\frac{4W_1^\circ}{h}-\frac{h}{2\pi^2 I_0 u}$$

one obtains

$$u=0.00711,$$

here, again, an agreement within the errors of observation.

On the whole one may feel that this is satisfactory evidence of the necessity for introducing half parameter numbers into the formulation of these bands. Such evidence has been made available by the measurement of this faint band which allows so straightforward an application of the combination principle.

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ON THE COSMIC ORIGIN OF THE RADIOACTIVE SUBSTANCES IN THE ATMOSPHERE

By HERMANN BONGARDS

ABSTRACT

The decomposition products of radium, actinium, and thorium in the atmosphere.—The presence of the emanations of the radioactive elements in the earth's atmosphere has been attributed hitherto to the *exhalations of the soil* and the rocks. There have been very few careful measurements for the free upper atmosphere, but it was known that the disintegration products from the soil were sufficient to account for the ionization observed near the ground.

Comparison of observations made at different places.—Observations made by the author in 1913 at Lindenberg, by means of steel wires from 5 to 15 meters in length, carried to altitudes of 4000 meters by kites, showed an unmistakable dependence of the quantity of emanation present upon the barometer at the surface and the temperature of the air strata measured. A period of twenty-seven or twenty-eight days in the variations observed suggested the sun as the source, since this is approximately the period of rotation of the sun. This suggestion was corroborated by a study of the calcium clouds shown by spectroheliograms taken between September 25 and October 12, 1913. Observations made at Manila, Philippine Islands, during the same period of time, by I. R. Wright and O. F. Smith, show that the fluctuations at the two places were the same. The author concludes therefore that *the sun is the source of the emanations*, and not the soil as hitherto believed.

The dissemination of the decomposition products of the emanations of radium, actinium, and thorium in the atmosphere was first established by J. Elster and H. Geitel.[1] As a consequence of this discovery, variations are observed in the emanation content of the atmosphere in many parts of the earth. The especially large quantities of emanation in the air in the upper layers of the earth's surface, and also in caves and cellars, suggest that their origin should be sought in the soil. The variations of the emanation content in the atmosphere were explained by the change of exhalation from the soil; and the connection that had already been established between the emanation content and such meteorological phenomena as insolation, precipitation, and variations of air pressure leads one back to the influence which these phenomena would exert on the exhalation from the ground. The observed fact that the soil and stones themselves are radioactive appears to support this hypothesis. But it seems that, in such investigations

[1] *Physikalische Zeitschrift*, **2**, 590, 1901; **3**, 305, 1902; **4**, 96, 522, 1903.

of the soil and its stony contents, methods of measurement are not always used which exclude the absorption of atmospheric emanation before and during the process of the experiment. Only isolated observations of the emanation content of the atmosphere at high altitudes are available at present, and often these are contradictory.

Starting with the hypothesis that the emanation comes from the earth, investigations upon mountain peaks would not be suitable for drawing conclusions as to the emanation content of the free atmosphere. Measurements in flying bodies would offer the only mode of attack. Such measurements have been undertaken by H. Brandes[1] in kites, and by H. Fleming[2] in balloons. But the methods that they used are not suitable for yielding quantitative results. Consequently, today we do not have any estimate of the quantity of emanation that is mixed with the free air at high altitudes.

This question is, furthermore, of the greatest significance in the explanation of the ionized state of the atmosphere, and of the theory of atmospheric electricity. The fact that the quantities of radium and its products of disintegration contained in the earth's atmosphere are sufficient to produce the total ionization observed near the ground follows from the ionization balance, described by E. von Schweidler and K. W. F. Kohlrausch.[3]

In 1913, during the period from July 29 to December 2, in Lindenberg (lat., 52° 12′.5; long., 14° 7′.5 west), the author attempted to observe the variations with the time in the radioactive content of the free atmosphere. Steel wires from 5 to 15 meters in length were carried up by kites to heights of 4000 meters. Since they were grounded and accordingly charged negatively with respect to the surrounding air, under the influence of the earth's field, they received a deposit of positively charged disintegration products of emanation. The strength of this deposit was measured, after landing, in the ionization chamber of an electrometer. A description of the method and a preliminary statement of the results were published soon after the completion of the measurements.[4] The final compilation of

[1] Dissertation, Kiel, 1905. [2] *Physikalische Zeitschrift*, **9**, 801, 1908.

[3] L. Graetz, *Handbuch d. Electr. und d. Magn.*, Leipzig, **3**, 234, 1915.

[4] *Die Arbeiten d. Kgl. Preuss. Aeron. Obs. Lindenberg*, **9**, 414, 1913.

the results followed after the close of the war, and was published with a detailed exposition of the methods of calculation.[1] A graphical summary of all the single observations (ninety-eight in number) was also given, and showed an unmistakable dependence of the emanation content upon the change of air pressure at the ground and the potential temperature of the stratum of air measured. At that time, valid arguments were made against the prevalent conception that the relation, so frequently observed, between air pressure and variations of amount of emanation, could be traced back to an exhalation from the ground modified by pressure changes.

The relation of the emanation content to temperature (which is a little less evident in the lower layers of the atmosphere) might give rise to the question as to whether the heat liberated in the disintegration of the radioactive substances entered into the phenomenon, and, therefore, directly acted upon the air pressure. A rough calculation having shown that such an effect was not probable, it will be assumed that a corpuscular radiation penetrating into the atmosphere brings in atoms of emanation, on the one hand, and also energy absorbed by the air in the form of heat, on the other hand. A clearly perceptible periodicity, at times, of a period of from twenty-seven to twenty-eight days, suggested the sun as a possible source of this radiation, since this was approximately the period of rotation of the sun. A further support of this hypothesis comes from a parallel consideration[2] of these results and a series of photographic exposures on the sun in the light of a calcium line, which were kindly put at our disposal by the Mount Wilson Observatory of the Carnegie Institution and the Yerkes Observatory of the University of Chicago. In the period from September 25 to October 2, 1913, an obvious relation was observed between the movement of the calcium clouds over the disk of the sun and the quantity of radioactive disintegration products in the earth's atmosphere. In order to obtain a further proof of this relation, measurement of the emanation content by a flying machine, with simultaneous spectroheliographic exposures, was proposed.

[1] *Physikalische Zeitschrift*, **21**, 141, 1920.

[2] H. Bongards, *Physikalische Zeitschrift*, **24**, 16, 1923.

While attempting to carry out this plan in spite of the unfavorable economic situation, the author discovered a paper by I. R. Wright and O. F. Smith,[1] which previously had not been accessible to him because it appeared during the war. These observers carried out measurements upon the emanation content of the atmosphere from July, 1913, to July, 1914, at Manila, Philippine Islands. Their method consisted in separating the emanation from the air by cocoanut charcoal, and gave quantitative results, instead of relative results such as were obtained by the wire method used in Lindenberg. During the common period of observation, of about four months, the observations in Manila are not so numerous as those in Lindenberg. The observations in Manila took place on thirteen different days during this period. On nine of these dates, observations were also made in Lindenberg. In three other cases, the observations in Lindenberg occurred on the day succeeding those in Manila. The measurements in Manila gave average values over a period of twenty hours, the air current being drawn through the charcoal from 1 P.M. of one day to 9 A.M. of the succeeding day. In Lindenberg, an observation lasted only two hours. Accordingly, a comparison of the two sets of observations would be more reliable if, for Lindenberg, the average of the readings on two successive days were taken. Such averages were made in the eight cases in which there were values for comparison. In three other cases, only the values on the succeeding day were used. Up to the end of September 8, which fell on a gap in the Lindenberg measurements, there were comparison observations in Lindenberg for all of those in Manila. These observations are given in Table I, and are represented graphically in Figure 1. The times, in the units indicated, are plotted as abscissae, and as ordinates the relative or absolute values of the emanation content. It is seen that the curves change together. This is all the more extraordinary and convincing since it has to do with a comparison of results of two entirely different modes of observation. That the agreement is accidental appears to be excluded, for the number of twelve observations distributed arbitrarily over a space of time of more than three months is too great. Furthermore, the position of the two places on opposite sides

[1] *Physical Review*, (2) **5**, 459, 1915.

of the earth, and under wholly different climatic conditions, with a difference in latitude of 37,° does not allow the conclusion that simultaneous meteorological conditions could have produced these simultaneous results.

TABLE I

Date	Manila	Lindenberg		
1913	Cr×10¹² Radioactive Equivalent per Cu. Meter (Curie ×10¹²)	Saturation Current in Static Units ×10⁶ per Sq. Cm of the Surface of the Active Wire		
	Mean	Single Obs.	Sum	Mean
July 28	14.5	.....	.....	0.66
29	.....	0.66	.....	.....
Aug. 4	23.6	1.91	3.36	1.68
5	.....	1.45		
18	39.5	10.65	17.61	8.80
19	.....	6.96		
25	19.6	1.50	3.58	1.79
26	.....	2.08		
Sept. 1	49.7	13.00	.....	13.00
2	.....	.....	.....	.....
8	17.3	.....	.....	.....
9	.....	.....	.....	.....
22	53.4	.....	.....	.....
23	.....	6.07	.....	6.07
29	52.0	15.24	37.54	18.77
30	.....	22.30		
Oct. 13	17.1	1.83	5.87	2.93
14	.....	4.04		
20	77.1	3.48	12.11	2.93
21	.....	8.63		
27	92.2	9.09	19.54	9.77
28	.....	10.45		
Nov. 3	49.9	3.86	5.64	2.82
4	.....	1.78		
10	75.4	.....	.....	3.90
11	.....	3.90	.....	

Therefore, it appears to be absolutely necessary to abandon the hypothesis that the variation of the emanation content of the atmosphere can be ascribed to changes of the exhalation from the soil. Accordingly, we must also give up the hypothesis that most of the emanation in the atmosphere comes from the earth's surface. Inasmuch as the source of emanation cannot be wholly in the atmosphere itself, we cannot avoid the assumption of a cosmic

origin for it. The sun would naturally be considered as the most probable source, and it would be assumed that corpuscular radiations are emitted from the sun which are carriers of emanation atoms. Since these atoms presumably possess positive charges, we accordingly have the foundations of a theory for the vertical current from the air to the ground, the drop of potential through the atmosphere, and the ionization of the atmosphere.

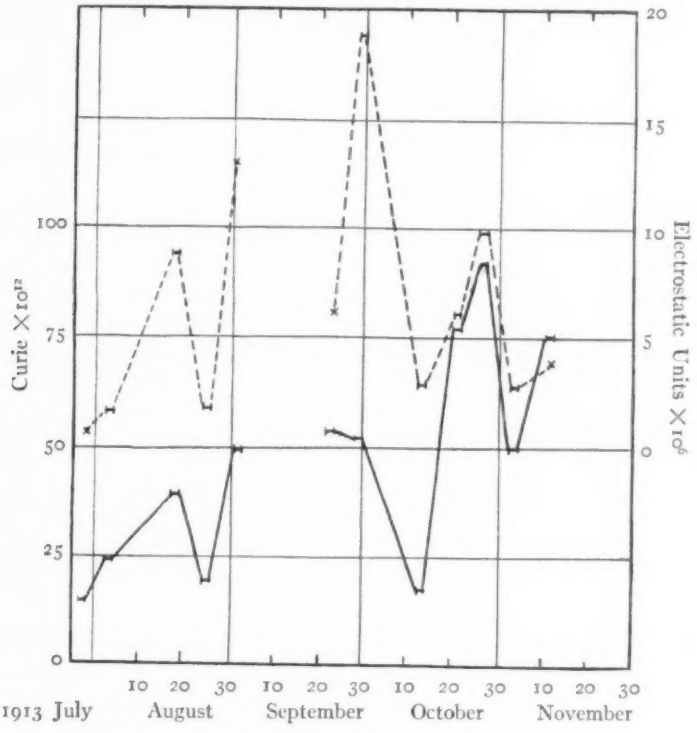

FIG. 1.—Lower curve, Manila; upper curve, Lindenberg

A further proof of this hypothesis would offer no insuperable difficulties. It would only be necessary to carry out simultaneous measurements of the emanation content near the ground and in the free atmosphere at numerous places suitably chosen. In addition, spectroheliograms of the sun should be made. The compilation of the information thus obtained would be sufficient to complete

the chain of proof for the solar origin of the emanation in the air. The significance of this knowledge in its bearing upon atmospheric electricity, terrestrial magnetism, meteorological and astrophysical problems is so great as to make the necessary expense of securing it appear small.

HAMBURG-GROSSBORSTEL
June 1923

ON THE DOUBLE STAR 9 ARGUS. A CORRECTION

In Vol. **58**, October 1923, page 144, *for* $\left(\frac{m_1}{m}\right)$ *read* $\left(\frac{m_1}{m_2}-\frac{\Delta m}{2m_2}\right)$ where $\Delta m = m_1 - m_2$ and $m_1 > m_2$, m_2 here designating the mass of the smaller star, which was called m in the original paper.

The term due to Δm is small only when the mass ratio is close to one. In the case of 9 Argus, this term equals -0.2 and the mass ratio, m_2/m_1, is therefore not 0.6 but 0.4 (page 145).

OTTO STRUVE

ERRATUM

Vol. **58**, July, 1923, in the article on Edward E. Barnard by Edwin B. Frost:

Page 31, third line, *for* Padang Padang *read* Solok.

REVIEWS

Newcomb-Engelmann's Populäre Astronomie, Sechste Auflage. Edited by H. LUDENDORFF, with the collaboration of G. EBERHARD, E. FREUNDLICH, and A. KOHLSCHÜTTER. Leipzig: Wilhelm Engelmann, 1921. Large Octavo, 24×18 cm. Pp. xii+889. Figs. 240.

We welcome this new addition of what we regard as the best general descriptive work on astronomy. It is based on Professor Simon Newcomb's classical *Popular Astronomy* which appeared in 1878 and of which, unfortunately, no revision has been made since 1882. The masterly presentation by Newcomb made a fine impression throughout the world, and the German translation was undertaken by Rudolph Engelmann, previously an astronomer at the Leipzig Observatory. It was published in 1881. Eleven years later a second edition was prepared by Engelmann's friend, H. C. Vogel, then director of the Potsdam Observatory, who included in the work the important progress made in astrophysics in the interim. In 1905 the third edition appeared, also edited by Vogel. The fourth edition (1911) was edited by Paul Kempf, with the assistance of G. Eberhard, H. Ludendorff, and K. Schwarzschild. This edition was exhausted in a space of three years, and the fifth appeared in 1914, also under the editorship of Kempf. In its various editions the work has thus had the benefit of the careful scrutiny of the above array of able astronomers at the Potsdam Observatory who have in each edition brought the book thoroughly up to date. In spite of the many additions made necessary by the progress of the science, the editors have endeavored to prevent the volume from reaching undue size. Thus the fifth edition exceeded the third by 88 pages; and the present volume is only 53 pages larger than its predecessor, the fifth edition. This has involved great discrimination in adding new material and leaving out that which is obsolete. In spite of the number of times the book has been worked over, the editors have lived up to their intention of retaining, just as far as they are valid today, the original statements of the American author, and a person who is sufficiently acquainted with the English language can read Newcomb's words in many places in this edition.

The tables are inserted in the text at the places where the particular subject is being described, and, while not exhaustive, represent adequately our present knowledge. Thus, on page 599 we find a table of radial velocities of 206 stars of third magnitude and brighter; and on

page 203 the parallaxes of 57 of the nearest stars, with their distances in light years and their magnitudes. Among other useful tables we may name the list of 42 stars of second magnitude and brighter, and those giving the computed orbits of 56 binary stars having periods of less than 120 years, the orbits of 67 spectroscopic binaries, and the mass functions for 51 such orbits. The tabular data and the numerical values given in the work can be particularly depended upon, by reason of the repeated revisions. We have noted a slip on page 713, where the linear velocity of rotation of the Andromeda Nebula, N.G.C. 224, at a distance of 2′ from the center, is given as 88, where it should be 58, kilometers per second. On the same page there seems to be also a misunderstanding about the rotation of the Andromeda Nebula, which was actually found to vary in a linear manner from the center outward, and not just as stated in this book. The discussions of star streaming, of the structure of the universe, and of cosmogony in general, are sane, clear, and logical. The statement of the problems as to the character of the spiral nebulae appears to us reasonable. The brief biographical sketches of deceased astronomers who have made important contributions to our science have been retained and constitute a useful section of the work.

The book is well bound in moleskin.

Since the above was written we have learned that the edition above referred to, of which 6000 copies were printed, was exhausted at the end of 1922. This, in itself, is sufficient and surprising evidence of the popularity of this work among readers of the German language. A seventh edition was published at the beginning of the present year. Aside from the correction of errors and the revision of some tables, the seventh edition differs from the sixth chiefly in the inclusion of an appendix (Nachtrag) of 20 pages, intended to cover the main items of astronomical progress in the last two years. This brings the total number of pages of the seventh edition to 902. The reviewer has read this supplement, but has not seen the main body of the seventh edition. The price has been set at 23 Swiss francs, or about $4.50, for the bound volume; and 20 Swiss francs for the work in paper binding.

We have also received definite information that a translation of this work, based on the seventh edition, is at last to appear in English. It is being undertaken by Dr. Henry Meier of Centre College, Danville, Kentucky, who was employed in the Nautical Almanac office under Professor Newcomb soon after his arrival from Switzerland, and who was also Professor Newcomb's assistant from 1885 to 1896. He is thus qualified for preparing this American edition. It is certain that this edition in English will be warmly welcomed and widely used.

E. B. F.

GENERAL INDEX TO *ASTROPHYSICAL JOURNAL*, VOLS. XXVI–L (1907–1919)

The Editors announce with pleasure that a General Index to Volumes XXVI–L (1907–1919) of the *Astrophysical Journal* has been prepared by Professor Storrs B. Barrett, of the Yerkes Observatory, and is now ready for distribution.

This General Index is uniform in style with the General Index to Volumes I–XXV (1895–1907), which was also compiled by Mr. Barrett and appeared in 1908. It is arranged by subjects and by authors, forming a volume of 116 pages, and is of the same format as this *Journal*.

From our own experience in the use of the first General Index, we can speak with assurance of the value of this second General Index to all users of the *Journal*.

The University of Chicago Press has fixed the price of the new index at $2.50, in paper covers, and makes a special offer, until April 1, 1924, of the two General Indices for $3.25.

To subscribers whose set of the *Journal* does not include the early volumes, the first General Index will serve as a bibliography of the papers appearing in those volumes, many of which are now out of print.

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